GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

5 July 1966

National Aeronautics & Space Administration
John F. Kennedy Space Center
Kennedy Space Center, Florida 32899

Attention: Mr. Carl Lennon, INS-323

Subject: Monthly Progress Report No. 1, Project A-946, "A Study of Certain Propagation Anomalies in Radio Frequency Signals," Contract No. NAS10-3809, Covering the Period from 6 June to 30 June 1966.

Gentlemen:

The majority of the first reporting period has been devoted to: (1) the design and construction of a RF-to-flame-plasma coupler for evaluating the electromagnetic properties and scaling potentialities of flame-plasma seeding, and (2) the establishment of instrumentation for powering and measuring the nonlinear properties of plasma media either totally sustained by RF sources or sustained by conventional methods and subjected to relatively large amounts of RF power. Preliminary tests will be made in closed configurations to determine the similarity of plasmas from various sources. If it can be shown that seeded flame and glow discharge plasmas exhibit similar electromagnetic properties, all radiated tests will be performed on glow discharge columns rather than rocket exhaust columns for reasons of economy and ease of instrumentation. Current theories on electromagnetic behavior in plasma media seem to indicate that the method of generating the plasma is not significant and that such similarity will be obtained if electron concentrations can be pushed high enough through seeding techniques.

The broadband coupler being built for use with the oxy-hydrogen rocket engine consists of a three-inch ID aluminum tube some three feet long in which is coaxially mounted a coupling helix wound on a slip-cast silica tube some 1 1/2 inches in diameter and 18 inches long. The rocket exhausts through the silica tube and thence through a silica venturi which jet-pumps cooling air around the outside of the coupling helix. In addition, a gas coolant can be pumped through the tubular windings of the helix itself if the venturi cooling feature is not sufficient. The helix is terminated at either end in a type N panel jack mounted in the aluminum shell.

Shop work on the coupler is complete and the models are presently being transformed into silica counterparts. These components will be completed and testing started in approximately two weeks. Some further delay may be encountered because of damage sustained by the rocket engine which must be repaired prior to operation.

The taper-matched coaxial line coupler designed and built during the previous contract period has been used to sustain argon glow discharge using radio frequency energy alone. This condition of excitation simulates antenna breakdown in plasma-laden atmosphere of low pressure and enables the nonlinear study of such media. Notch filters have been constructed for use in high power RF measurements to help eliminate intermodulation within the sensitive equipment used for nonlinear studies. This same apparatus is necessary for tests using high-power RF to establish the upper limit of linear proportionality in conventionally sustained plasma media.

During the next reporting period, the variations in harmonic level for input variations up to several watts will be measured using the taper-matched coaxial line coupler. Preliminary testing of the coupler for the rocket engine will begin as soon as the components of the coupler are available. Experiments to determine the effect of dipole resonance on power absorption will be set up using argon glow discharge plasma as a convenient medium.

Respectfully submitted:

R. D. Trammell, Jr.
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

9/8/66

A-946

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

6 September 1966

9-6-66

National Aeronautics and Space Administration
John F. Kennedy Space Center
Kennedy Space Center, Florida 32899

Attention: Mr. Carl Lennon, INS-323

Subject: Monthly Progress Report No. 3, Project A-946, "A Study of Certain Propagation Anomalies in Radio Frequency Signals," Contract No. NAS10-3809, Covering the Period from 1 August to 31 August 1966.

Gentlemen:

During the third reporting period, harmonic data have been obtained at high rf signal levels using the rocket engine coupler with argon discharge tubes. The silica parts have been fitted within the coupler and test runs initiated on the rocket engine proper. Antenna patterns and VSWR data have been obtained for the specially built dipole antenna employing an argon discharge as one arm of the dipole. Only weak harmonic-signal radiation has been detected for large fundamental levels fed to the special dipole at its $\lambda/4$ resonant frequency (147 MHz).

Second, third, and fourth harmonic levels have been measured at both helix ports of the rocket engine coupler using glow discharge sustained by dc and rf power sources. RF sustaining power is introduced through a TM mode wave launcher at the engine end of the coupler tube. This coupling technique allows the measurement of products generated within the plasma using two modes of launch simultaneously. The fundamental signal is placed on the TM launcher and the harmonics detected at the helical coupler ports. Under certain conditions of dc sustaining current, large harmonic outputs were detected for +20 dbm input signals. Second and third harmonic levels peaked at +3 dbm and -6 dbm respectively for a +100 ma dc sustaining current and +20 dbm fundamental power at 147 MHz. With no dc current, (plasma excited by rf alone at levels between +30 and +40 dbm) second, third, fourth, and fifth harmonic levels of -1.5 dbm, -4.0 dbm, -15.5 dbm, and -30.0 dbm respectively have been measured. All harmonic levels measured at the helix for fundamentals introduced at the TM launcher are multi-valued functions of input signal power and dc excitation current.

When the fundamental is introduced at a helix port and the harmonics are measured at the same port, the experimental slopes of input vs output harmonic level are in close agreement with the theoretical slopes for the first three harmonics for fundamental levels below +20 dbm. The slopes fall significantly below the theoretical after +20 dbm, +25 dbm, and +30 dbm for the second, third, and fourth harmonics respectively. These are apparently the saturation levels for the primary generating terms associated with this plasma medium.

Preliminary test firings of the oxy-hydrogen rocket engine through the silica-lined helix coupler revealed excessive heating of the helix. Water cooling of the helix proper was found to be necessary. The forced air cooling feature is sufficient to carry heat from the aluminum housing. The slip-cast silica tube, however, will not withstand run times in excess of some 20 seconds as it fuses and loses its thermal shock characteristics. A test run of 30 seconds softened and glazed the first silica tube so that it fractured on the next firing. It is felt that runs of 20 seconds will be sufficient for data collection and spare tubes are presently being cast and fired so that frequent changes may be made.

The special plasma antenna produces an excellent dipole radiation pattern at 147 MHz which is its $\lambda/4$ resonant length. VSWR characteristics with frequency change are typical of those for a normal dipole antenna. Radiated second harmonic levels have been detected with a probe antenna for input levels between 1 and 4 watts at 147 MHz.

During the next reporting period, tests will continue with the oxy-hydrogen engine to determine the electrical characteristics of the engine exhaust plasma. The effect of NaCl seeding will be measured during these tests. Fundamental and second harmonic levels and radiation patterns will be obtained for the plasma dipole antenna in an effort to determine the parameters which affect the radiated conversion efficiency. Some difficulty may be encountered in obtaining valid patterns because of the lack of anechoic chamber facilities in the range from 50 to 400 MHz. Open-field measurements of the type contemplated require special licence by the FCC, the time for issuance of which has been estimated at two to four months.

Respectfully submitted,

R. D. Trammell, Jr.
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

3 October 1966

National Aeronautics and Space Administration
John F. Kennedy Space Center
Kennedy Space Center, Florida 32899

Attention: Mr. Carl Lennon, INS-323

Subject: Monthly Progress Report 4, Project A-946, "A Study of Certain Propagation Anomalies in Radio Frequency Signals," Contract No. NAS10-3809, Covering the Period from 1 September 1966 to 30 September 1966.

Gentlemen:

During the fourth reporting period, preliminary data concerning radiation pattern and generation level for harmonics produced by a center-fed plasma dipole have been obtained using a screen room and hooded antenna measurement technique developed at Georgia Tech. Limited insertion loss measurements have been obtained at 240 MHz and 480 MHz for NaCl seeded rocket exhaust using the silica-lined helix coupler built for this purpose. Excessive heating and shock-front damage continue to hinder this phase of the research effort.

Construction was begun on a large-area plasma test facility using argon glow-discharge tubes placed at right angles to form a 4 foot by 4 foot slab of plasma. This facility will be used to study harmonic generation properties under the influence of high-level radiated fundamental signals. In addition, two plasma dipoles of smaller scale than the first model were constructed for additional tests of macroscopic resonance on harmonic generation.

The data obtained from a center-fed dipole, one arm of which is a glow-discharge plasma, provides oblique evidence that the harmonic level obtained is a function of the resonant length of the dipole. Measurement techniques are not yet refined enough to obtain positive evidence of a significant dependence on the resonant length of the plasma column. It should be noted, however, that the pattern obtained for the generated harmonic compares well with that obtained for the dipole when driven by a signal identical in frequency with the generated harmonic. The radiated level versus frequency curves made under like conditions show sufficiently favorable correlation to warrant further study of this phenomenon. Further testing of the dipole antenna has been delayed because of test equipment and facility scheduling. These tests as well as tests using the plasma slab will be resumed in another two weeks when the facilities become available.

Tests on the oxy-hydrogen rocket engine at 240 MHz and 480 MHz showed no significant insertion loss through the coupler helix for the unseeded flame plasma. At 480 MHz the addition of NaCl to the flame caused an immediate insertion loss of some 63 db. At 240 MHz the NaCl seeding caused an immediate increase of some 33 db. of insertion loss, showing a definite transfer of radio frequency energy to the plasma column in both cases where seeding was employed.

The results obtained at these two frequencies almost exactly match the insertion loss results obtained at the same frequencies using a glow-discharge in 2.5 Torr argon as sustained by a TM-mode-launched 147 MHz signal at 6 watts. These results are promising to the effort of correlating flame and glow-discharge plasma characteristics; however, the insertion loss measured at 240 MHz with the seeded rocket exhaust may be in question because the silica tube fractured during this run, causing the ultimate destruction of the helix and the majority of the useful span of data. The resulting damage to the coupler has only recently been repaired. This and former fractures of silica tubes has necessitated a change in the tube design which has held up further engine testing prior to this report. New tubes are now on hand and testing will be resumed later in the week.

During the next reporting period, data will be obtained on harmonic generation in a seeded flame plasma as well as further VSWR and insertion loss characteristics over the operating band. Further testing of plasma dipoles will be undertaken when the equipment becomes available. Radiated tests using the plasma slab will be started using 400 MHz signals in excess of 100 watts.

Respectfully submitted,

R. D. Trammell, Jr.
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION
ATLANTA 13, GEORGIA

4 November 1966

National Aeronautics & Space Administration
John F. Kennedy Space Center
Kennedy Space Center, Florida 32899

Attention: Mr. Carl Lennon, INS-323

Subject: Monthly Progress Report 5, Project A-946, "A Study of Certain Propagation Anomalies in Radio Frequency Signals," Contract No. NAS10-3809, Covering the Period from 1 October to 31 October 1966.

Gentlemen:

During the fifth reporting period, preliminary data has been obtained for fully radiated tests of harmonic generation in a slab of 2.5 Torr argon plasma. Probe calibration and plasma dipole patterns have been obtained in twenty megacycle steps from 60 MHz to 800 MHz in the anechoic chamber located here at Georgia Tech. A portion of the harmonic patterns have been obtained over the same range but the two watt level required to make these patterns tends to interfere with the pattern recorder and degrade the data. Tests for harmonic generation, insertion loss, and impedance matching have been conducted on the oxygen-hydrogen engine with three seeding contaminants. To date conclusive evidence of harmonic generation in the seeded exhaust at either 100 MHz or 220 MHz has not been obtained.

The 4 foot by 4 foot plasma slab was placed in the center of the anechoic chamber and subjected to radiation at 400 MHz from an 8 element yagi antenna. A 16 element yagi was placed both directly behind the plasma slab and at 90 degrees to the incident radiation. In both positions the level of the 800 MHz radiation from the slab was well above detection sensitivity for a fundamental power of less than 5 watts into the 8 element yagi. With the plasma bank turned off, no 800 MHz signal could be detected. Absolute levels for this experiment are not presently available since this test was not calibrated and only intended to determine the ability to perform the desired test.

A dipole with $\lambda/2$ resonance at approximately 220 MHz consisting of one metal and one plasma arm has been tested in the anechoic chamber between 60 and 800 MHz. Patterns at the fundamental frequency resemble those expected from a metal dipole of fixed length. Patterns of a similar antenna of all metal construction have not been completed so that correlation is not possible to date. Several harmonic radiation patterns have been completed, however, and correlation to the fundamental pattern is fairly good below the tuned frequency of the dipole. Little or no correlation has been obtained between fundamental and harmonic radiation patterns well above the tuned frequency.

The power available to the plasma dipole for the harmonic tests is one watt at the fundamental frequency in all cases. Since matching is not constant at all frequencies, the actual power accepted by the antenna is not known. At a frequency of 280 MHz, (140 MHz input frequency) the peak level of the radiated harmonic was equivalent to a -11 dbm signal into a tuned dipole and the pattern obtained was very similar to that obtained when the antenna was center fed at 280 MHz. This is the frequency of the largest harmonic level measured using this antenna and represents a definite peak in harmonic production in the plasma. Its correlation to antenna length is not yet possible because no comparable data are available for an antenna of different length. There is oblique evidence that the equivalent electrical length of the plasma arm is somewhat longer than the equivalent electrical length of the metal arm for the antennas being utilized.

Insertion loss measurements have been made at 100 MHz, 240 MHz, 480 MHz, and 800 MHz using the silica lined helix coupler on the rocket exhaust with NaCl seeding. The curve connecting these loss values approximates that obtained with an RF excited glow discharge plasma in a similar helix coupler. The mismatch at the helix ports, however, is greater for the seeded flame than the glow discharge. Potassium carbonate and aluminum powder seeding provide relatively more loss and a slightly better match than NaCl (particularly so in the case of aluminum powder seeding); however, the potassium carbonate is difficult to feed and the aluminum powder coats the inner wall of the silica tube with aluminum metal and oxides.

Although the insertion loss characteristic of the flame plasma is very similar to that for low pressure glow discharge, the harmonic generation properties appear to be considerably different. Tests involving three coupling arrangements have produced no positive evidence of harmonic generation in the flame plasma seeded with NaCl when driven with up to two watts of fundamental power at 100 MHz and 220 MHz. No attempt has been made to detect harmonics with potassium carbonate or aluminum powder seeding as of this report. Only with hybrid injection of the fundamental and harmonic detection at port number 2 (farthest from the engine) has there been any harmonic measured whatsoever, and this at a level of -72 dbm. One cannot be certain whether this level, some 105 db below the incident fundamental, is a product of the plasma, a spurious response of the receiver, or harmonic leakage around the filter. If it is a harmonic product of the plasma, it falls 101 db below the fundamental power available to the plasma. The exact amount of the available power absorbed by the seeded flame plasma is not yet known.

Since the temperature of the flame plasma is sufficient to highly ionize NaCl and produce electron concentrations in the range of those for the low pressure glow discharge, the difference in the harmonic generation characteristics must lie in the pressure difference of the two media. The pressures in the flame plasma reach about 90 mm of mercury while those in the glow discharge are around 3 mm of mercury. The pressure could have forced the electron concentration far below that expected and it certainly could increase the losses encountered by both fundamental and harmonic signals. Since it is impractical to operate the test engine in a vacuum, no direct test of the significance of pressure can be performed. It cannot be concluded, however, that no interference will be generated by a rocket's exhaust based on the information thusfar obtained. A rocket exhausts into pressures varying from atmospheric to near vacuum. Further experimentation is required to determine whether or not the medium can be a significant generator of nonlinear products. It might be mentioned here that there is evidence of an effect of pressure on harmonic generation in a low pressure argon discharge. A change from 2.5 Torr to 3.0 Torr apparently lowered the harmonic level but increased the limit of linear proportionality between the fundamental and harmonic power levels. The experiment was performed with two tubes of different length, however, and this factor may have affected the results.

During the next reporting period, testing of plasma dipoles will be continued to determine the effects of length on the efficiency of second harmonic generation. Fully radiated tests will be performed on both the plasma dipoles and the plasma slab. These tests will include polarization and incidence angle effects on the radiated second harmonic level. Further testing of the rocket engine coupler will be undertaken to determine the matching conditions at the helix ports.

Respectfully submitted:

R. D. Trammell, Jr.
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

FINAL REPORT

PROJECT A-946

A STUDY OF CERTAIN PROPAGATION ANOMALIES IN RADIO FREQUENCY SIGNALS

R. D. TRAMMELL, JR. AND E. E. DONALDSON, JR.

Contract No. NAS10-3809

6 June to 6 December 1966

Prepared for
National Aeronautics and Space Administration
John F. Kennedy Space Center
Kennedy Space Center, Florida

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia

FINAL REPORT

PROJECT A-946

A STUDY OF CERTAIN PROPAGATION ANOMALIES IN RADIO FREQUENCY SIGNALS

By

R. D. Trammell, Jr. and E. E. Donaldson, Jr.

CONTRACT NO. NAS10-3809

6 June to 6 December 1966

Prepared for
National Aeronautics and Space Administration
John F. Kennedy Space Center
Cocoa Beach, Florida

FOREWORD

This report was prepared at the Georgia Institute of Technology, Engineering Experiment Station under Contract No. NAS10-3809 with the National Aeronautics and Space Administration, John F. Kennedy Space Center, Kennedy Space Center, Florida. The materials contained herein present the results of a six-month experimental study of the nonlinear properties of plasma media.

The program was conducted under the general supervision of D. W. Robertson, Head, Communications Branch. Acknowledgement is made to Messrs. R. L. Fitzwilson and R. W. Moss for their contributions in equipment construction and the measurement of the parameters required for this study.

Respectfully submitted:

Robert D. Trammell, Jr.
Project Director

Approved:

D. W. Robertson, Head
Communications Branch

ABSTRACT

A closed-system coupler of the coaxial helix type was developed for coupling radio frequency signals onto either glow discharge or seeded flame plasma columns. The coupler exhibited excellent power transfer and harmonic detection characteristics with 2.5 Torr argon glow discharges sustained with both rf and dc power sources. The characteristics obtained with seeded flame plasmas at atmospheric pressure were poor; a fact which appears to be based on the large pressure difference in the two media. Second harmonic levels of +5 dBm were measured using a 2.5 Torr argon glow discharge and a fundamental level of +22 dBm at a frequency of 147 MHz.

Radiation tests were conducted on plasma-metal dipole and plasma slab configurations built up of low pressure glow discharge tubes. The dipole configuration radiated peak second harmonic levels equivalent to a -25 dBm signal into a tuned dipole when subjected to radiated energy from a 2 watt source at fundamental frequencies near the resonant length (290 MHz) of the plasma dipole. The plasma slab configuration radiated peak second harmonic levels equivalent to only -40 dBm into a tuned dipole when subjected to the same 2 watt source at a 400 MHz fundamental frequency.

It is concluded that a rocket plume at atmospheric pressures will cause little or no interference to electromagnetic devices because of harmonic or intermodulation distortion generated within the flame. However, the launch vehicle discharges its plume into an increasingly rarefied atmosphere as it ascends, and the probability of interference appears to increase as the pressure is reduced.

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I. INTRODUCTION

The contents of this document comprise the findings of a continued study to establish an understanding of the phenomenon of intermodulation and harmonic distortion of electromagnetic waves in or on the surface of plasma media as it applies to the potential threat of interference from the nonlinear characteristics of plasmas associated with launch vehicles. The purpose of this study is to provide the NASA with a knowledge of the intermodulation and harmonic levels which might be generated when an electromagnetic wave propagates within or along the surface of a plasma medium, and to enable cognizant personnel to determine whether or not this source is a potentially serious interference threat. The scope of the research has been limited to theoretical and laboratory scale experimental investigations concerning the phenomena of intermodulation and harmonic distortion of electromagnetic waves in plasma media which simulate those created by a launch vehicle during flight. Experiments performed during this phase of the study utilize both conducted and radiated electromagnetic coupling techniques.

Experimental testing with low pressure argon glow discharge tubes in closed-system coupling setups has shown that plasma media can generate harmonic and intermodulation signals of a significant magnitude with input levels of one milliwatt and less.[1] One milliwatt corresponds to a maximum voltage gradient of about 0.1 volts per centimeter for the couplers that were utilized and represents a power density which could easily be reached in the space immediately adjacent to a launch vehicle. All of the tests performed under contract NAS10-2639 (previous study) were limited to the power levels available from standard signal generators (20 milliwatts) and were designed to establish the level and the probable origin of the harmonic or intermodulation distortion that was detected. Second harmonic levels were shown to increase as the square of the fundamental level (2 for 1 in dB) for values of fundamental level from that yielding a harmonic barely detectable above the noise to the maximum available output of the generator. Intermodulation distortion levels were also shown to follow the laws of the resistive mixer over the entire range of available fundamental input levels for glow discharge in argon under low pressures.

Tests utilizing a flame plasma generated by a small oxygen-hydrogen rocket motor and seeded with aluminum metal power provided little evidence of harmonic distortion due to the presence of the seeded plasma.[2] The electromagnetic coupling to the flame plasma was shown to be poor and it was assumed that a lack of sufficient coupling was responsible for the failure to detect positive evidence of harmonic distortion in the seeded flame plasma. Investigation of the coupler at a later date revealed aluminum deposits on the helix which probably contributed to the nonlinear distortion which was measured in these tests.

The plasma studies performed during the current six-month period were designed to extend the knowledge gained under contract NAS10-2639. A special high temperature helical coupler was designed and constructed to provide better electromagnetic coupling to seeded flame plasmas. Tests were conducted at high levels of fundamental power to determine the point above which the 2 for 1 relationship between second harmonic and fundamental levels became invalid in low pressure glow discharge plasmas. Radiated electromagnetic tests using dipole and slab plasma configurations were conducted to determine expected levels and direction of propagation of second harmonic signals generated in and radiated by the glow discharge plasma.

II. FACTUAL DATA

A. Harmonic Studies for High Level Fundamental Inputs with Glow Discharge Plasmas

The behavior of the level of a harmonic generated within or on the surface of a plasma column has been studied as a function of the conditions of excitation and fundamental power level for low pressure glow discharges in argon gas. Coaxial helix and coaxial line couplers have been used both singly and combined to study these properties for glow discharges sustained by direct currents and radio frequency sources. All measurements performed on glow discharges in closed system tests were taken from the positive column for plasmas under direct current excitation.

The levels of reflected second, third, and fourth harmonic were measured as a function of fundamental level using the TM wave coaxial line coupler developed under contract NAS10-2639.[3] The test setup for these measurements is shown by block diagram in Figure 1. The fundamental level from the Boonton 230A was varied between -10 dBm and +39 dBm; the latter is the maximum power level that can be presented to the Anzac H1 hybrid.

Two argon tubes of different length and absolute pressure were excited by constant direct currents calculated to provide essentially equal electron densities for both tubes. The behavior of the second, third, and fourth harmonic levels is shown by the curves in Figures 2 and 3. The fundamental and harmonic levels have been corrected to the TM launcher port and represent the levels at the plasma surface. It is noted that the theoretical slopes for the three harmonics (dashed lines) describe the behavior of the harmonic levels relatively well for small values of fundamental power. As

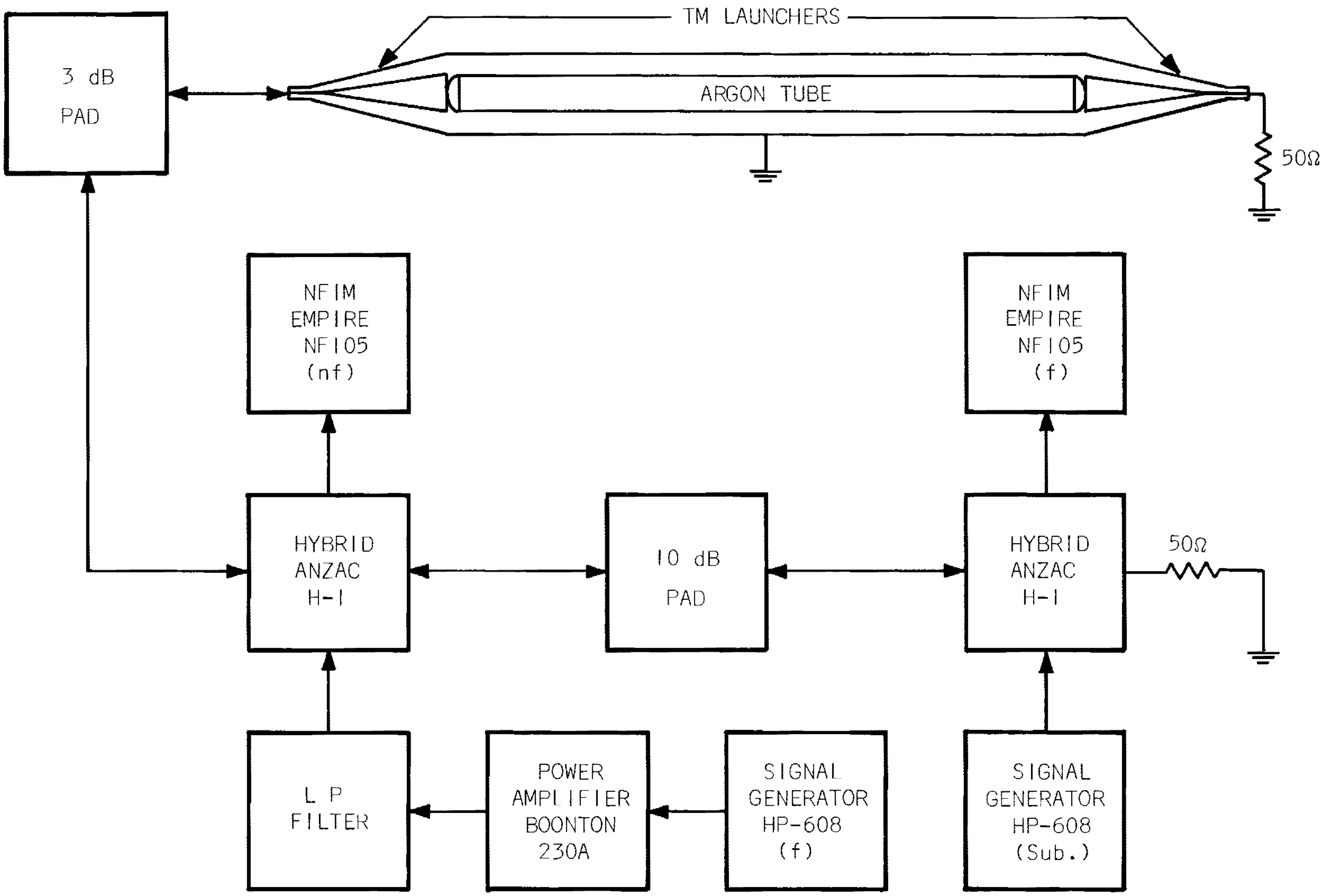

Figure 1. Test Setup for Measurement of Reflected Harmonic Levels Generated in the Coaxial Coupler.

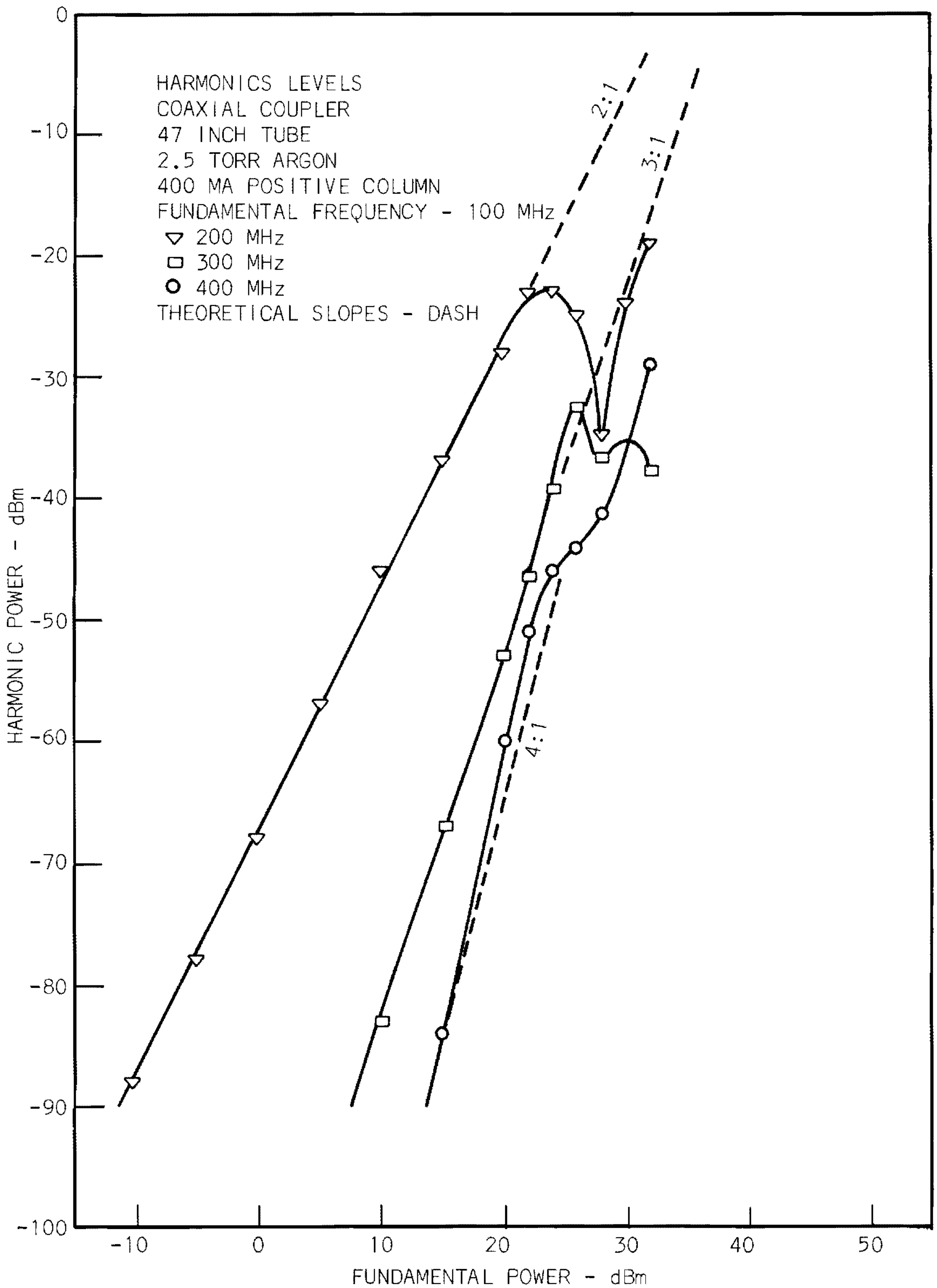

Figure 2. Reflected Harmonic Variations with Changes in Fundamental Power for the Coaxial Coupler at 2.5 Torr.

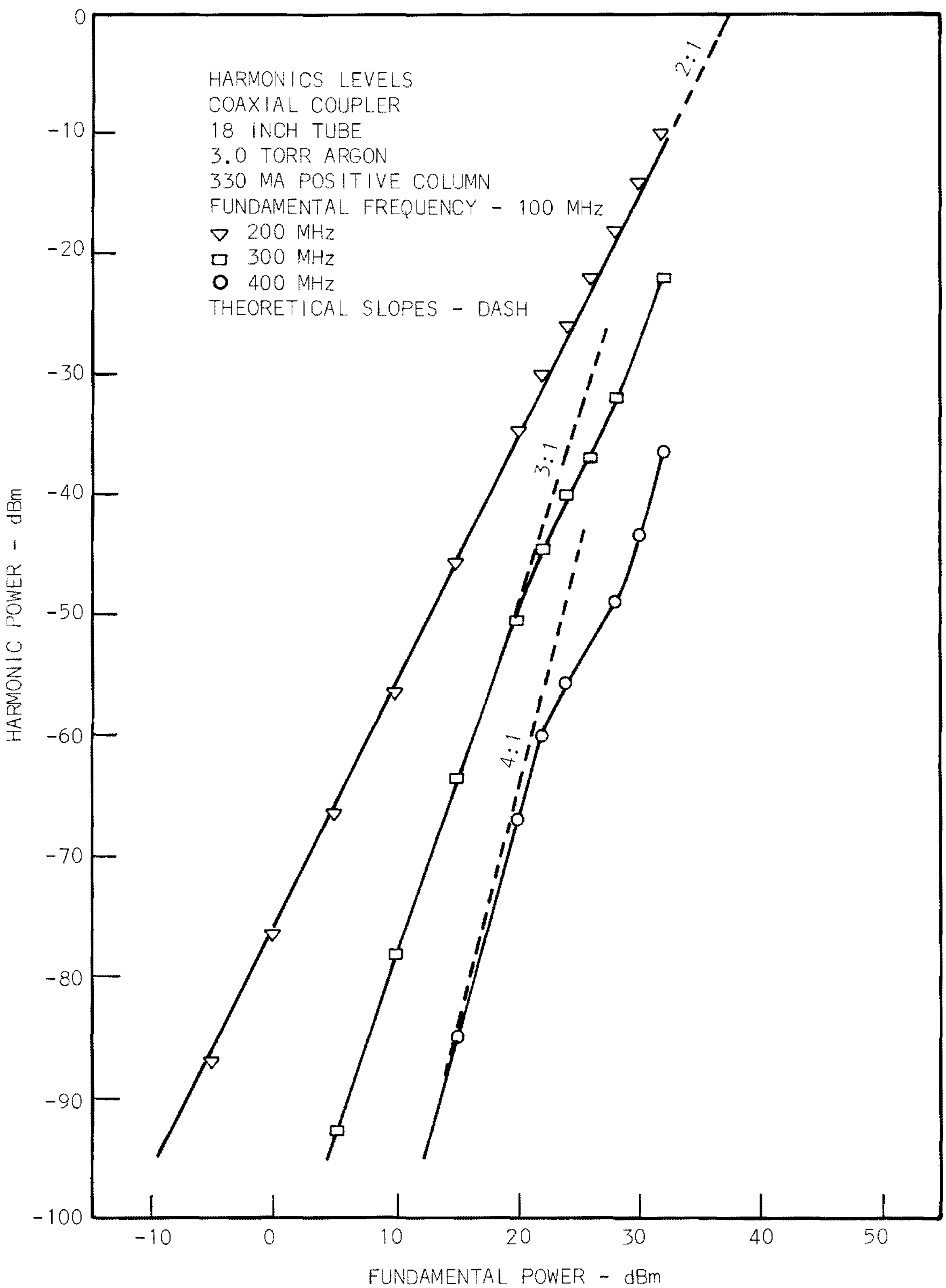

Figure 3. Reflected Harmonic Variations with Changes in Fundamental Power for the Coaxial Coupler at 3 Torr.

the fundamental power is increased, a break point is reached beyond which the theoretical slope is no longer valid. Of particular interest here are the differences in the behavior of the second harmonic for the two tubes. The second harmonic from the higher pressure tube exhibits a slightly lower point for point value over the range adequately described by the 2 to 1 slope, but apparently breaks away from the 2 to 1 slope at a significantly higher power level. Limitations on equipment prevented the location of this break point under the present effort.

The test setup shown in Figure 4 is arranged for the rapid accumulation of data using an automatic curve plotter. The same type of setup was also used to obtain data point by point by substituting a signal at the junction between port No. 1 (P_1) and the 3 dB pad. The coupling characteristics for the helical coupler used in these experiments are shown in the Appendix. The level of radio frequency excitation applied to the plasma at 147 MHz was adjusted for optimum matching characteristics at port No. 1 without regard for other considerations. Under these conditions of excitation, the visible glow extended from the TM launcher through the helix to perhaps two inches beyond the port No. 2 end of the helix. Radio frequency excitation in this manner provides a graded electron density along the axis of the helix which more nearly matches the conditions along the axis of a rocket plume. The coupling characteristics for rf excitation shown in Figures A-3, A-4, and A-5 of the Appendix demonstrate this fact in that the VSWR at port No. 1 more nearly falls on the 400 ma curve while at port No. 2, it more nearly approximates the 20 ma curve. The insertion loss characteristic for rf excitation is almost an average of the specific loss

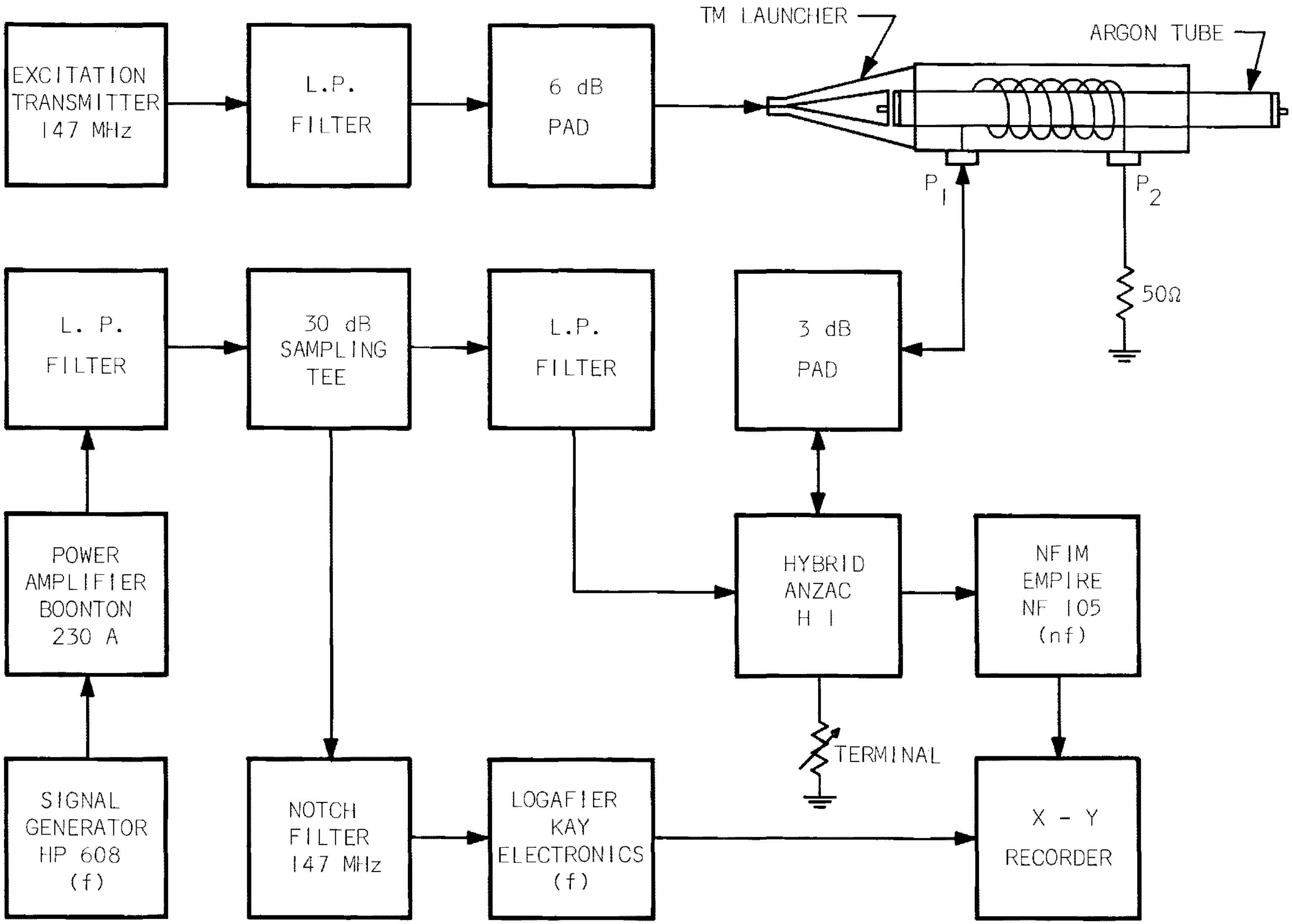

Figure 4. Test Setup for Measurement of Reflected Harmonic Levels Generated in the Helical Coupler.

characteristics measured at 400, 100, and 20 ma dc excitation. The rf insertion loss curve is also quite similar to that obtained with a flame plasma seeded with sodium chloride as shown in Figure A-6 of the Appendix.

The curves shown in Figure 5 were obtained using the point by point method of taking data and the general setup shown in Figure 4. The harmonics shown are grouped by harmonic number as designated by the slope indications. In this particular case, the levels measured within each harmonic grouping were very nearly the same for the 400 ma and 100 ma excitation values. The level of second harmonic generated under conditions of rf excitation fell below those shown for dc excitation. Indications from data not presented here imply that both higher and lower values of dc excitation will tend to fall in the range of the values shown for rf excitation in this specific test.

A condition of interest is noted in the curves of the fourth harmonic. At a value of +23 dBm of fundamental, two values of fourth harmonic were obtained depending upon the direction of approach. This hysteresis is indicated and the direction of approach is shown by the arrows. When taking data on a point by point basis, this type of effect is not usually caught unless the jump in value is large. Tests conducted at a later date using an automatic plotter verified that this effect could occur for all the harmonics and was most noticable at the lower values of plasma excitation. The limited dynamic range over which the plotting board could be operated made calibration very difficult and only the plot proceeding from maximum power to minimum power was recorded. The curves thus obtained were linearized by replotting and are shown in Figures 6, 7, 8, and 9 for

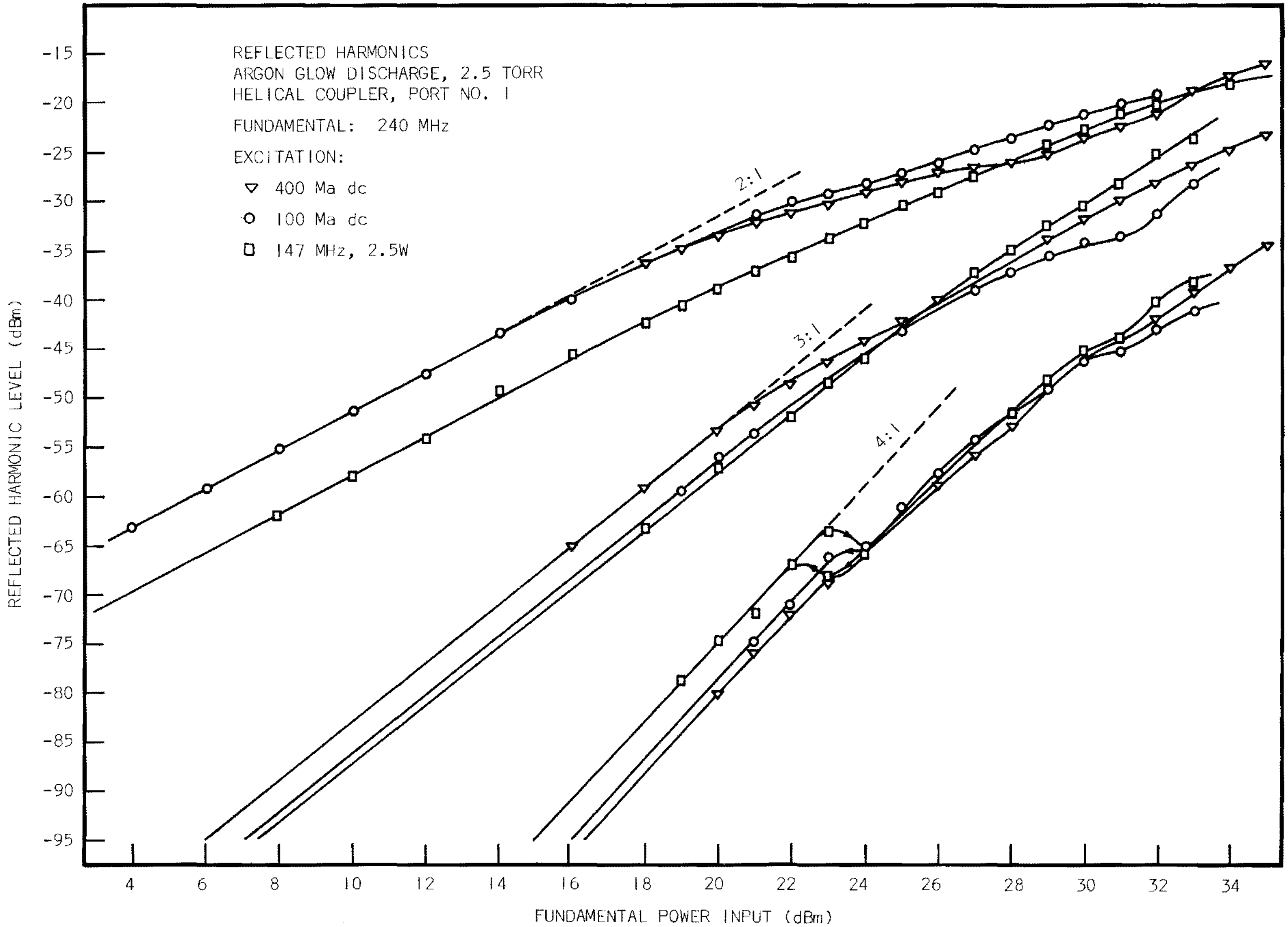

Figure 5. Reflected Second, Third, and Fourth Harmonic Level Variations with Changes in Fundamental Power and Plasma Excitation.

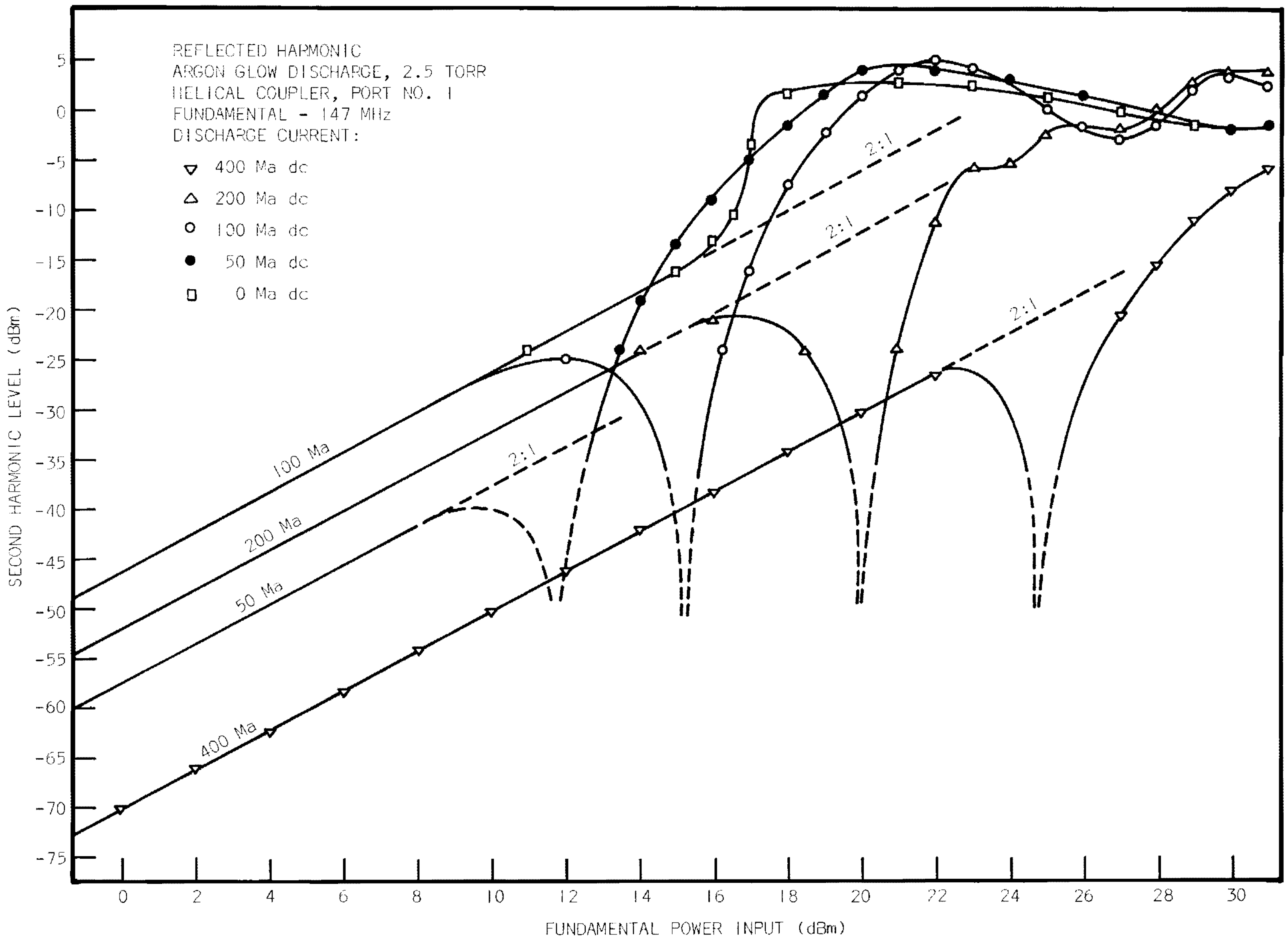

Figure 6. Reflected Second Harmonic Level Variations with Changes in Fundamental Power and Electron Density.

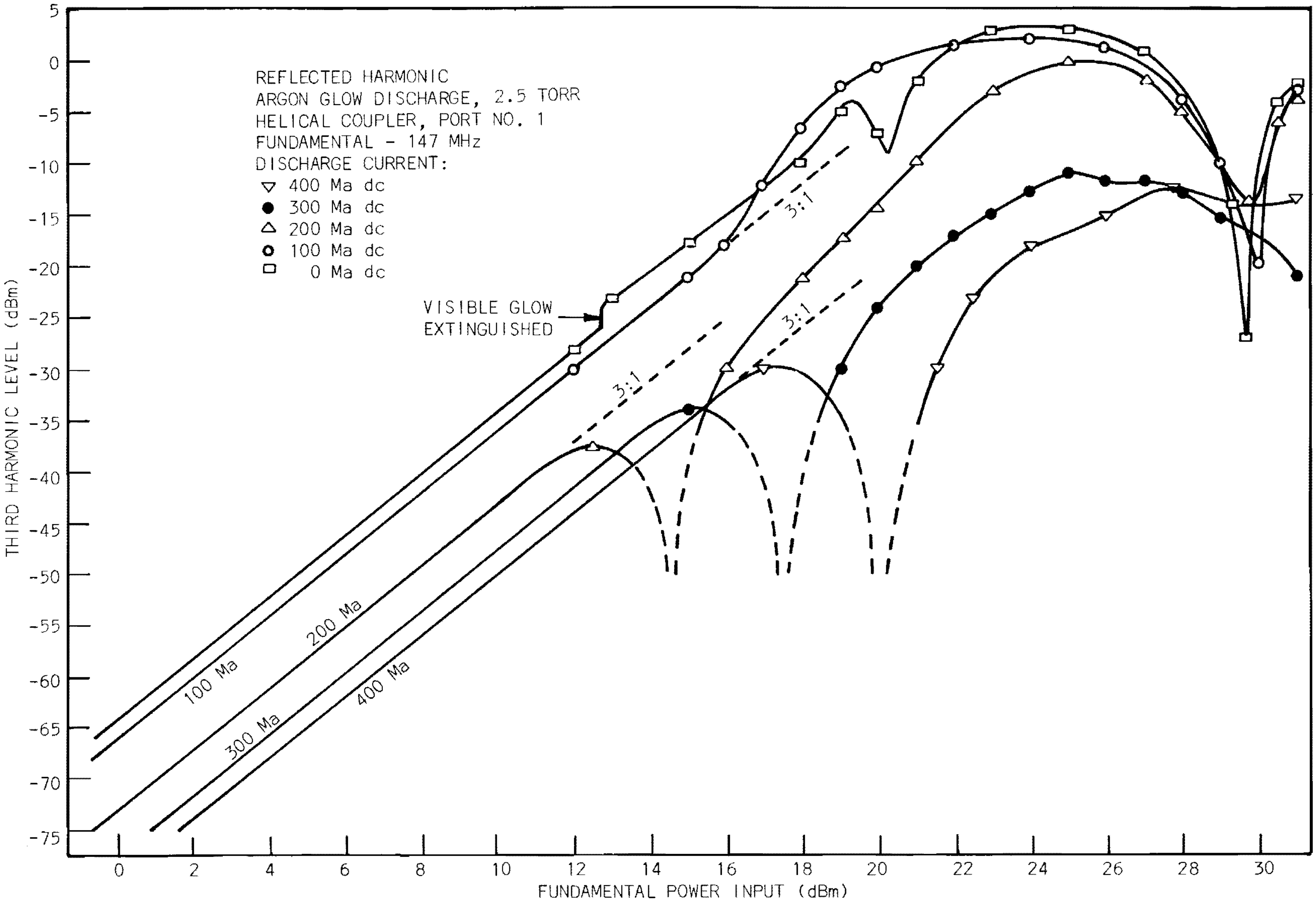

Figure 7. Reflected Third Harmonic Level Variations with Changes in Fundamental Power and Electron Density.

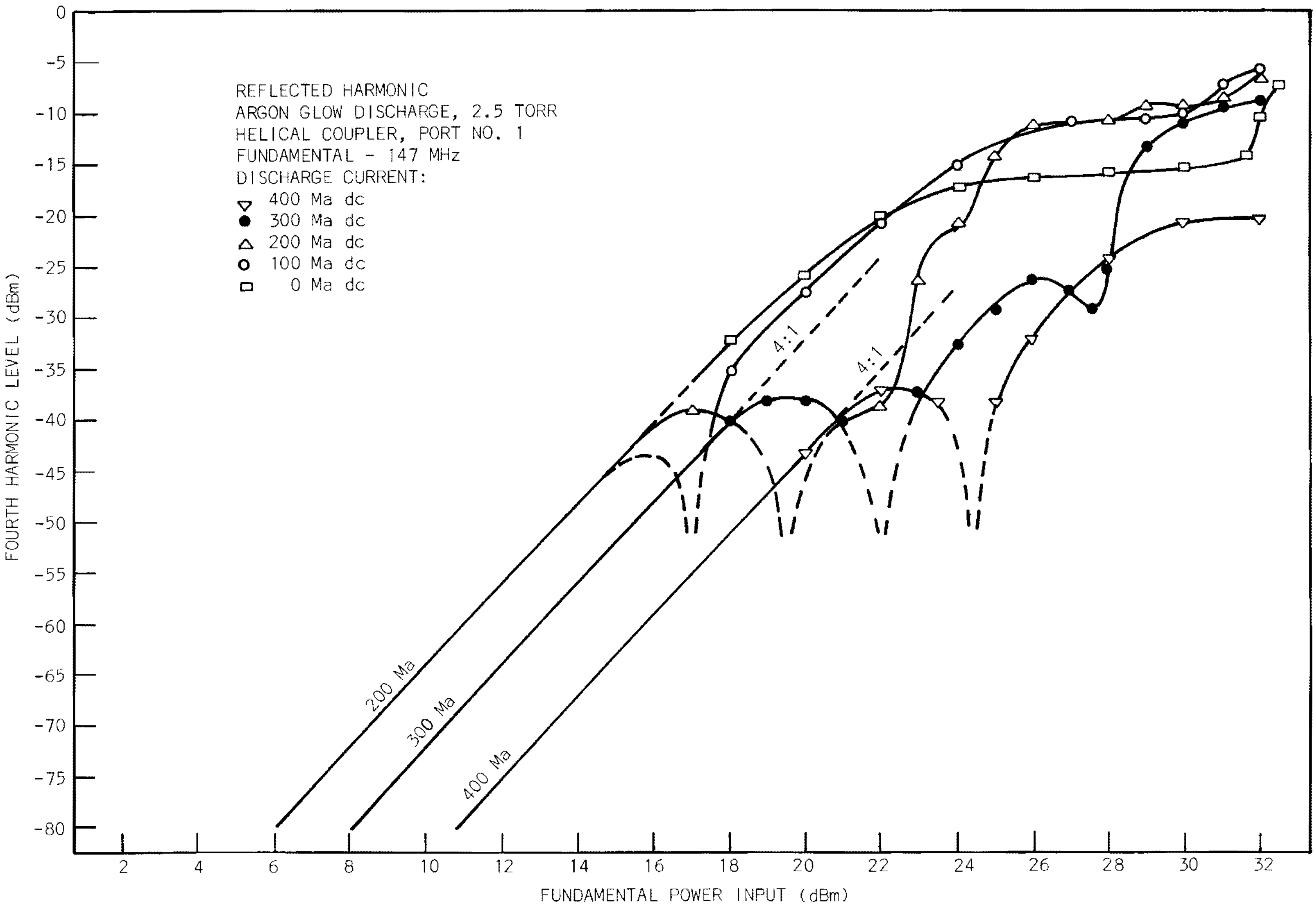

Figure 8. Reflected Fourth Harmonic Level Variations with Changes in Fundamental Power and Electron Density.

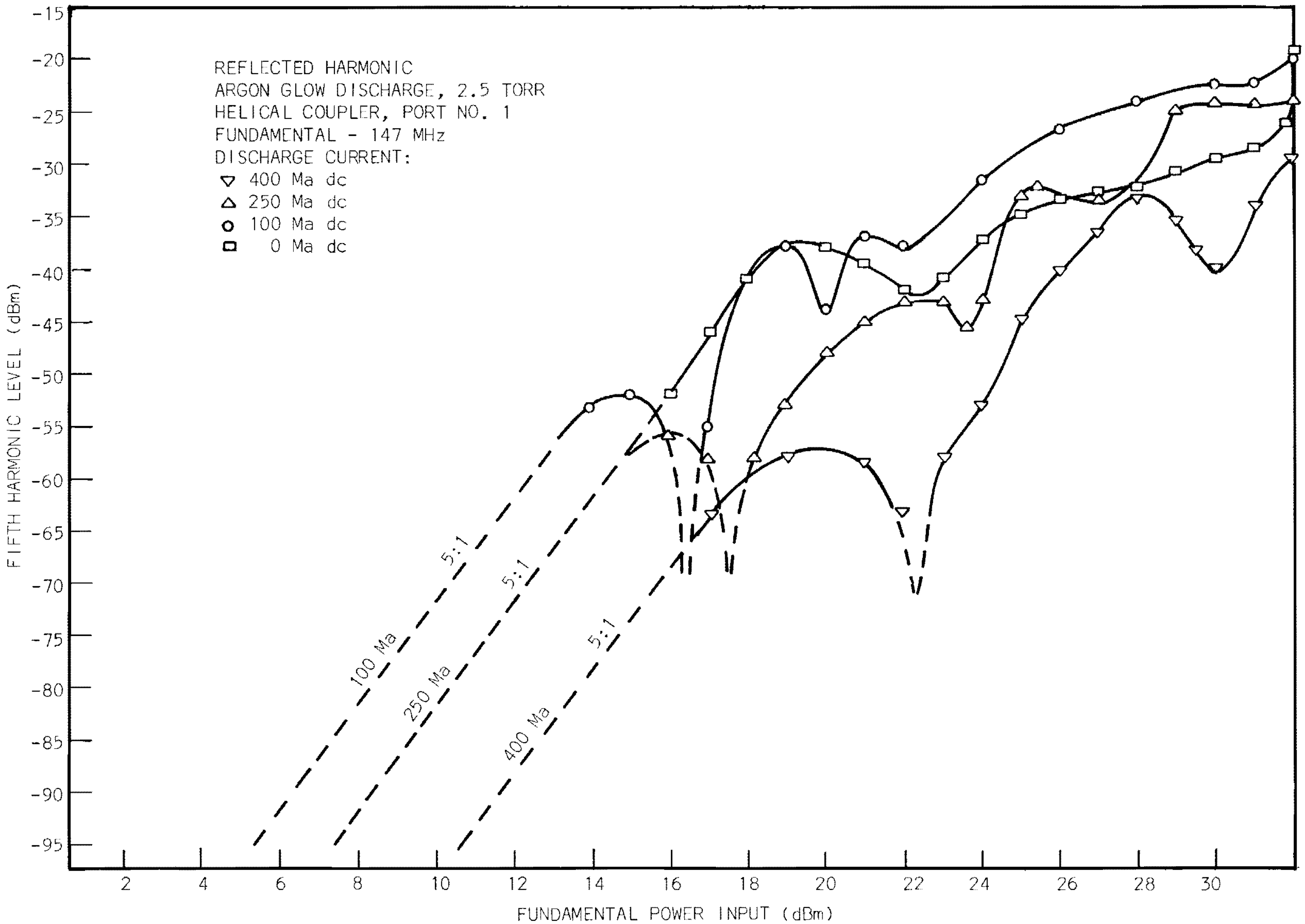

Figure 9. Reflected Fifth Harmonic Level Variations with Changes in Fundamental Power and Electron Density.

the setup of Figure 4. In all cases tested the harmonic levels obtained at the point of hysteresis were larger for ascending power levels. In fact, at the lower values of dc excitation, the maximum harmonic levels shown in Figures 6, 7, 8, and 9 were exceeded during the ascent to maximum fundamental power to the extent that the recorder pen was driven into the upper limit. The position of the hysteresis loop with respect to fundamental power level always occurred above the point at which the harmonic deviated from the theoretical resistive mixer slope.

L. A. Dysart reports a possible theoretical explanation for the hysteresis effects noted here.[4] The phenomenon may result from a negative slope region which occurs in the plot of electron temperature versus the absolute value of the electric field strength squared, divided by the radial frequency squared of an incident electromagnetic wave which is selectively heating the electrons. The position of occurrence of this phenomenon with respect to fundamental power level is a function of frequency, the constituents of the plasma, and the absolute pressure of the plasma. In the case of glow discharge plasma, the sustaining current level alters the magnitude of the hysteresis effect and may alter the position of occurrence slightly. The approximate values of E^2/W^2 for which hysteresis occurred in the present experiments fall into the range given in the referenced work.[5]

The behavior of the harmonic levels shown in Figures 6 through 9 is considerably more complex than that shown in Figure 5 and the maximum levels are larger within a common harmonic group. The dashed nulls indicate that the exact behavior is not known because these values lie outside of the calibrated range of the extremely nonlinear original curves. The straight line slopes shown at low input level were assumed on the basis of prior experimentation except where data points are given. The frequency for which these curves were plotted lies at a resonant coupling condition for the helix coupler. Only 0.02 watts of 147 MHz fundamental were required at helix port No. 1 to maintain a small region of visible glow at the helix center. The excellent coupling exhibited at this frequency may explain the large values of harmonic generated.

Considering the loss of power to the dispersive plasma medium, the fundamental nonlinear mechanism above the straight line break point may be reactive in nature. J. H. Krenz and G. S. Kino[6] have demonstrated that for low pressure plasma media, parametric oscillations may exist under certain conditions. In general, their conditions for optimum output require good coupling to the plasma, a low collision frequency, and a small electron density. The collision frequency is chiefly a function of the absolute pressure in the plasma tube while the electron density is related to both the pressure and the excitation current in the discharge tube. Coupling is a function of both the electron density[7,8] and the collision frequency.

A series of tests was conducted using both the TM launcher and the helix coupler as shown in Figure 10. The fundamental is coupled to the plasma using a TM launcher and both the fundamental and the harmonic are measured at helix port No. 1. Curves of the fundamental coupling from the TM launcher port to helix port No. 1 are shown for various conditions of excitation in Figure 11. For all dc excitation conditions the coupling was

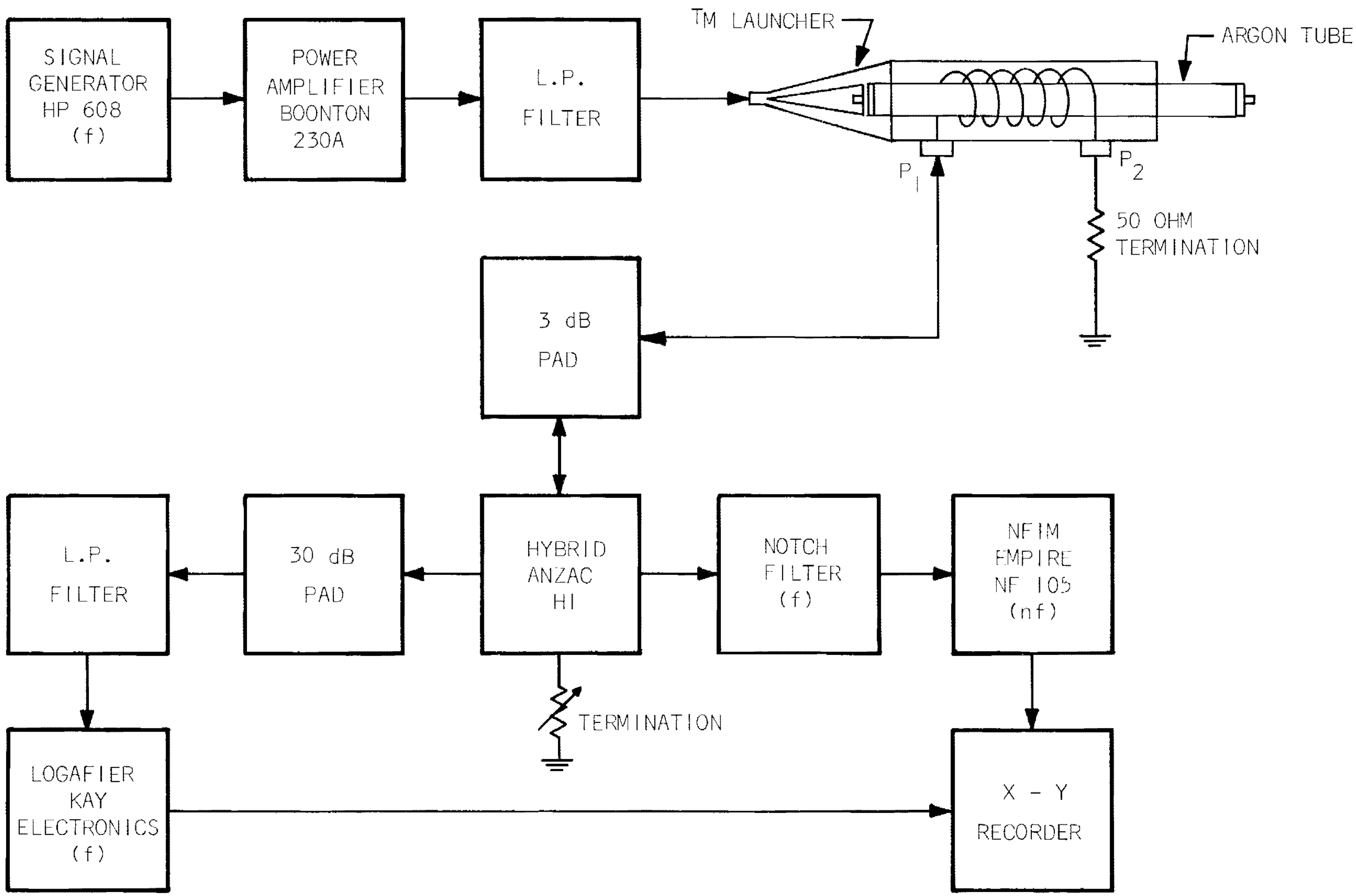

Figure 10. Test Setup for Measurement of Coupled Fundamental and Harmonic Levels.

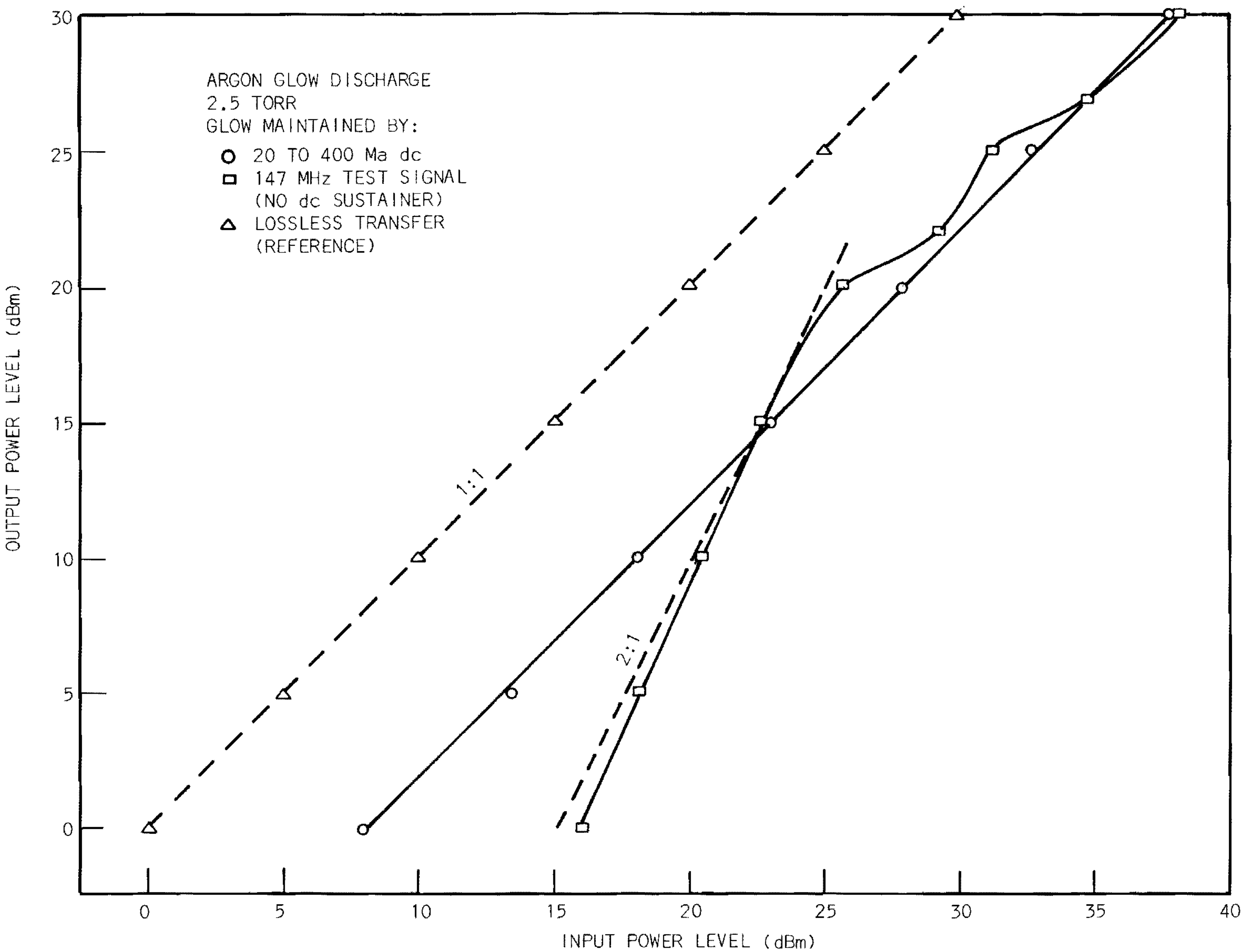

Figure 11. Fundamental Power Coupled from TM Launcher to Helix Port No. 1 at 147 MHz.

a constant 8 dB below the input level. When the excitation was furnished by the 147 MHz test signal alone, the output level varied approximately as the square of the input level until the glow reached the helix. The coupling was varied as the glow proceeded through the helix, and settled at the 8 dB figure as it proceeded beyond the port No. 2 end of the helix.

The second and third harmonic levels coupled out of helix port No. 1 are shown in Figures 12 and 13 respectively. It is interesting to note that the behavior of the harmonic levels under dc excitation is very similar to that obtained under the reflected harmonic tests shown in Figures 6 and 7 when referred to the fundamental level at helix port No. 1. For rf excitation (zero dc current), the low power slope is seen to be one unit smaller than that indicated in the reflected harmonic series. The condition is a function of the 2 for 1 slope in fundamental coupling noted for rf excitation in Figure 11 because the curves of Figures 12 and 13 are plotted with respect to the coupled fundamental level at port No. 1. The slopes are correct when taken with respect to the fundamental power input at the TM launcher. The curves indicate that harmonic generation at any point along a plasma column is a function of the fundamental level at the point of measurement.

B. Harmonic and Coupling Studies with Seeded Flame Plasmas

Tests using seeded flame plasmas were conducted with a miniture oxygen-hydrogen rocket engine which was seeded by blowing salts or metallic powders into the flame with dry nitrogen gas. The physical setup and characteristics of the helical coupler used in these tests are given in the Appendix.

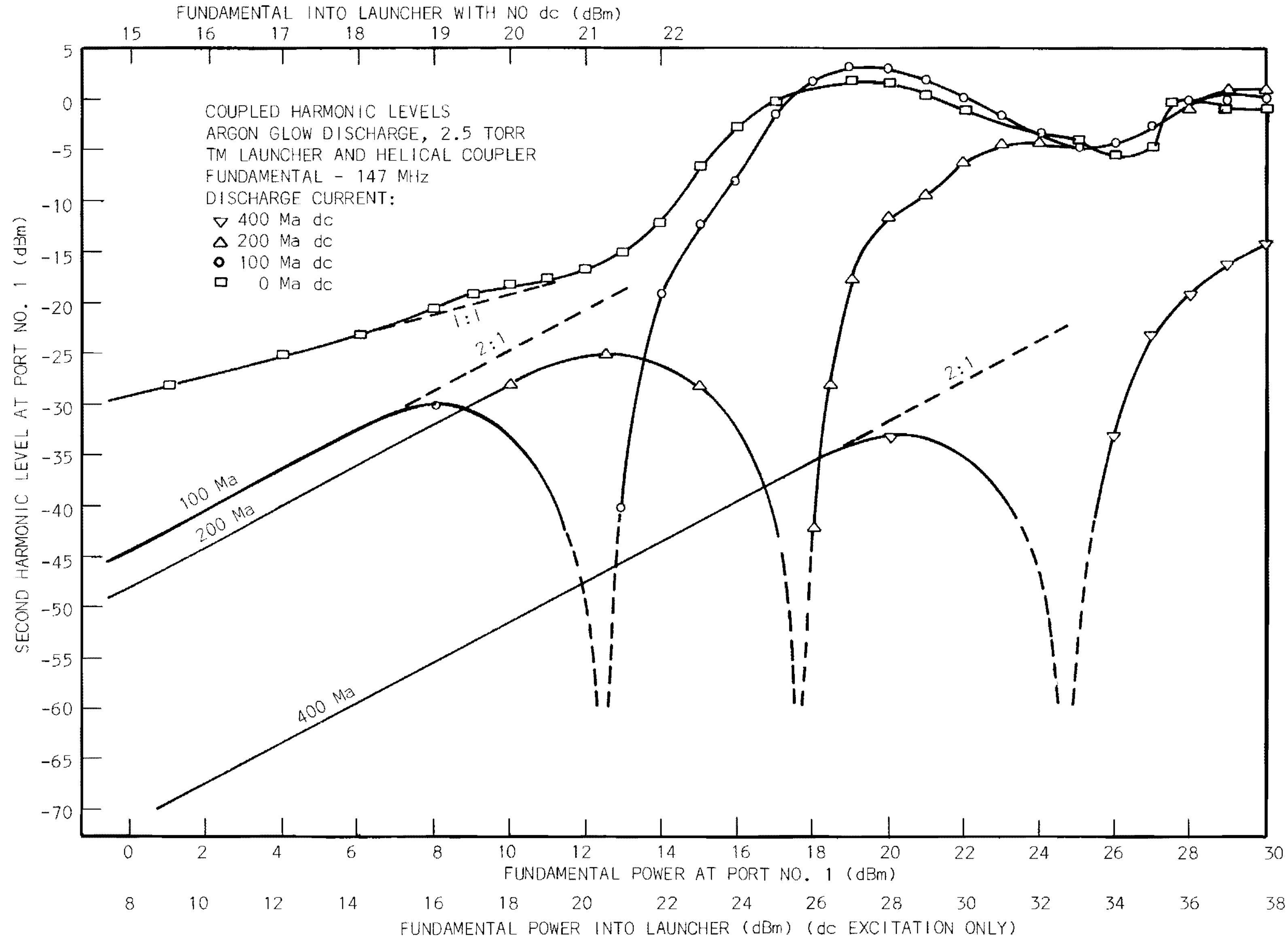

Figure 12. Coupled Second Harmonic Level Variations with Changes in Fundamental Power and Electron Density.

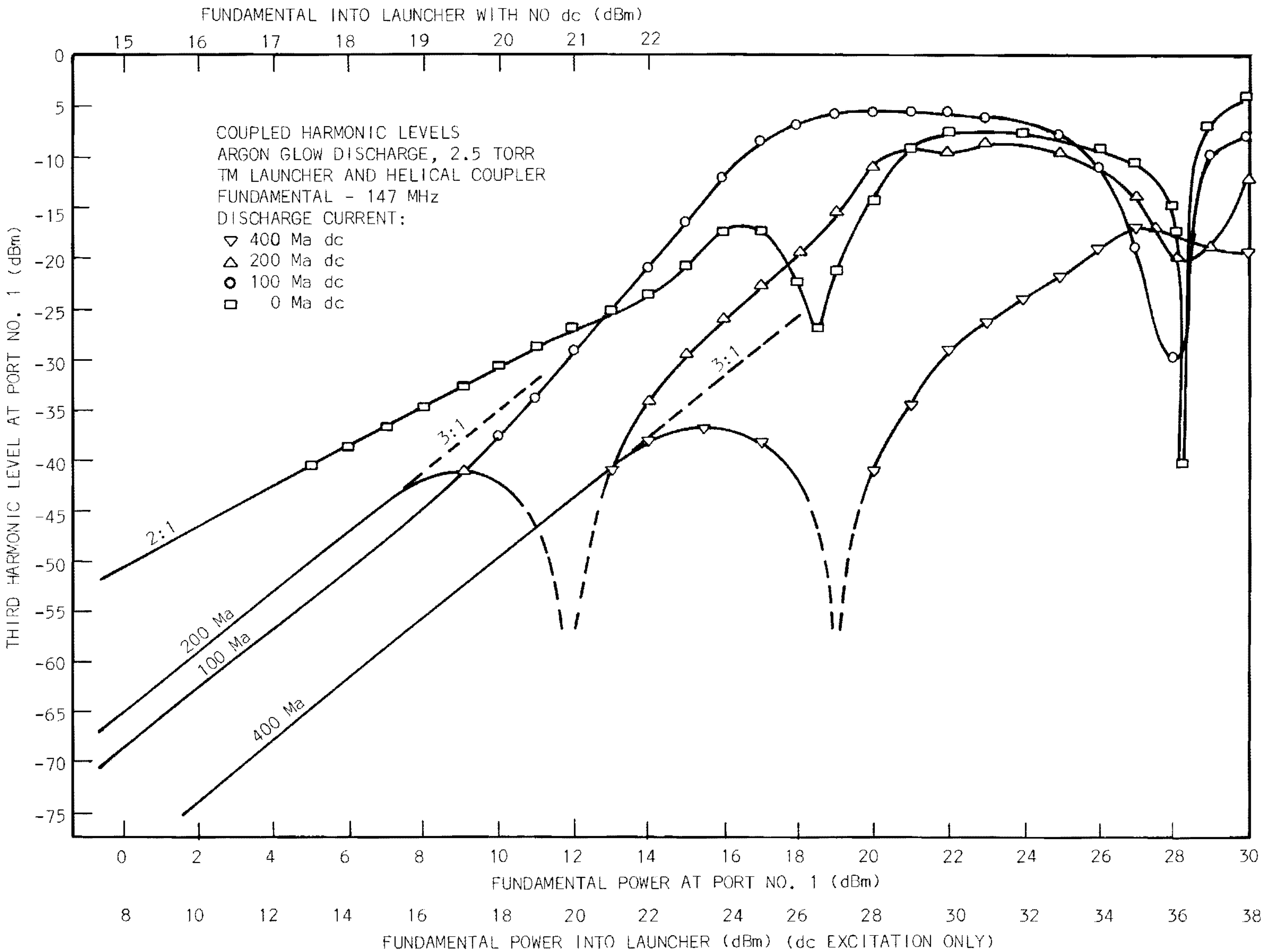

Figure 13. Coupled Third Harmonic Level Variations with Changes in Fundamental Power and Electron Density.

All data involving seeded flame plasmas were obtained through automated techniques because of limited run times of some twenty seconds maximum. The high temperatures encountered in these tests and the long periods required for cooling and equipment checkout resulted in the collection of only minimal amounts of data.

The tests discussed in Section A of this chapter were conducted with the helix wound directly against the glass envelope of the glow discharge tube which permitted close coupling of signals to the plasma within. Silica liners of a thickness comparable to the glass envelope of the argon tubes fractured upon firing the rocket. The thicker silica tubes which were required reduced the maximum possible coupling effectiveness of the helix.

A 12 inch by 1/2 inch glow discharge tube was attached to the end of a pole such that it could be pushed through the exit opening of the silica liner to lie within the coupling helix while in position on the rocket engine. This glow discharge tube was used for the comparasion measurements made in the following tests. It should be realized that these tests are not equivalent to those previously discussed for the glow discharge tubes because the coupling of signals is greatly diminished.

Tests were performed for flame plasmas seeded with sodium chloride, potassium carbonate, and powdered aluminum metal using the test setups indicated in Figures 14, 15, and 16. All of the seeded flame data presented by charts in this section were obtained for sodium chloride seeding. Figure 17 shows three single channel recordings typical of early data obtained with an X-Y plotter. Reflected data was limited to fundamental

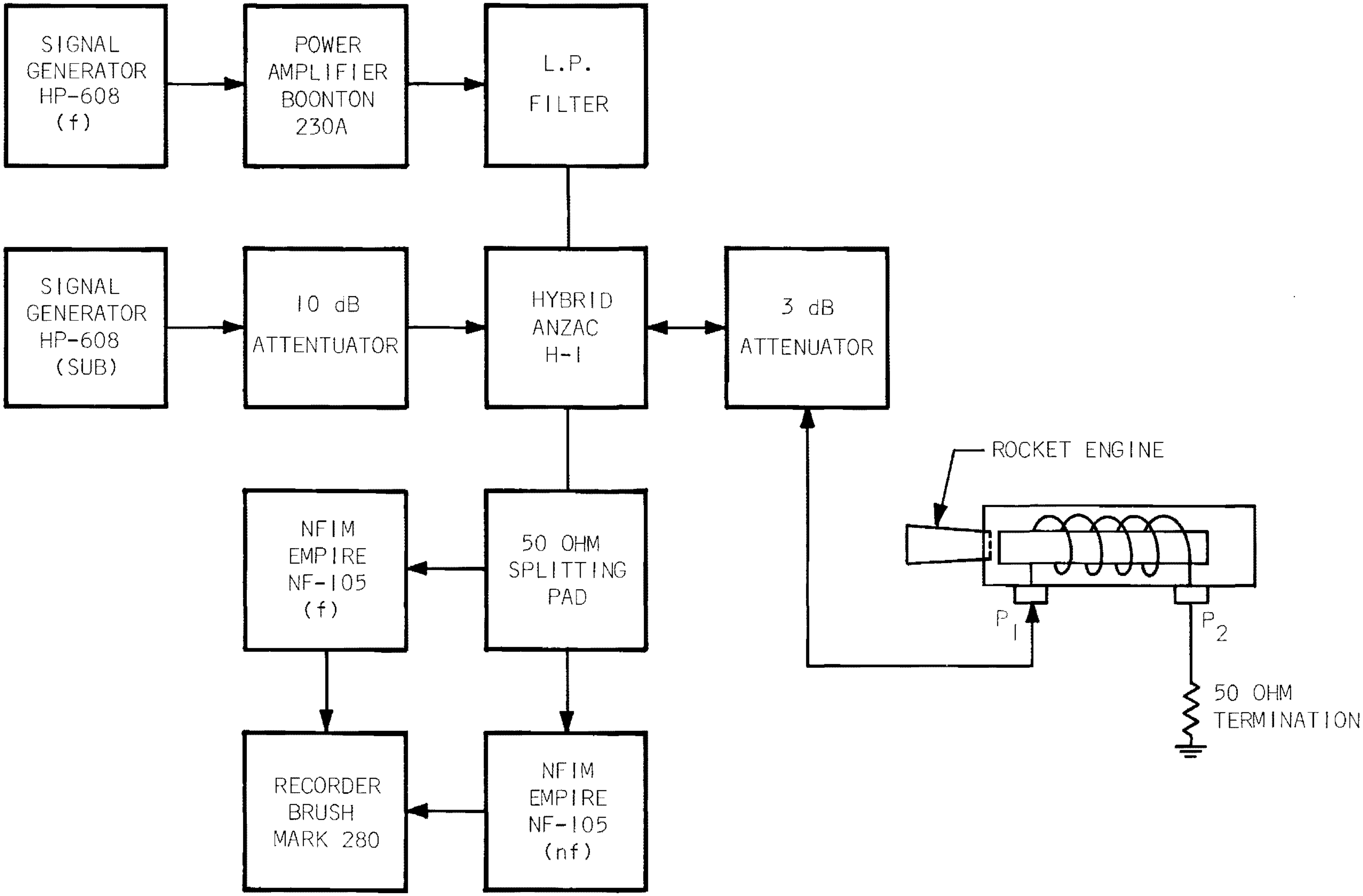

Figure 14. Test Setup for Measurement of Reflected Fundamental and Harmonic Levels.

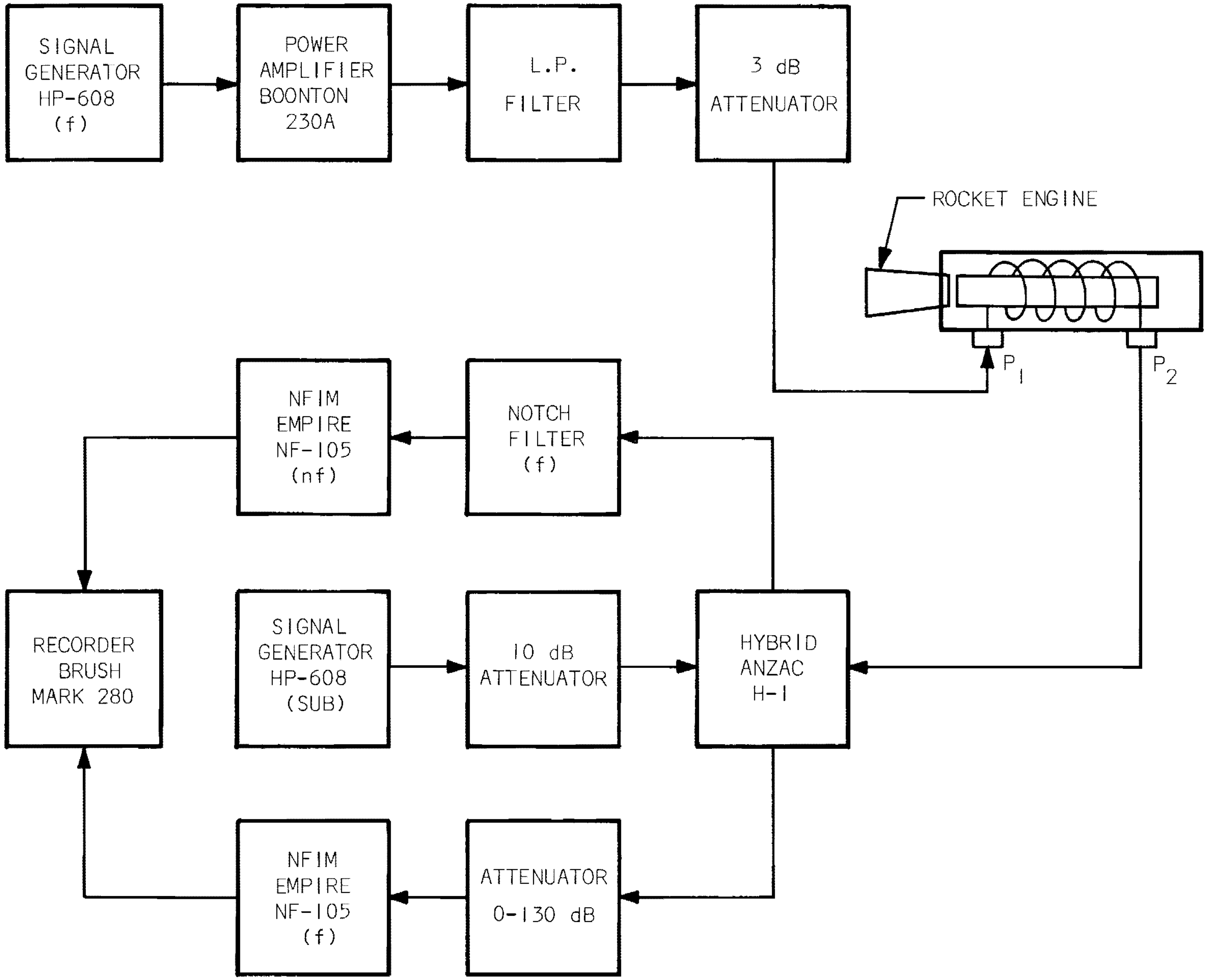

Figure 15. Test Setup for Measurement of Transmitted Fundamental and Harmonic Levels.

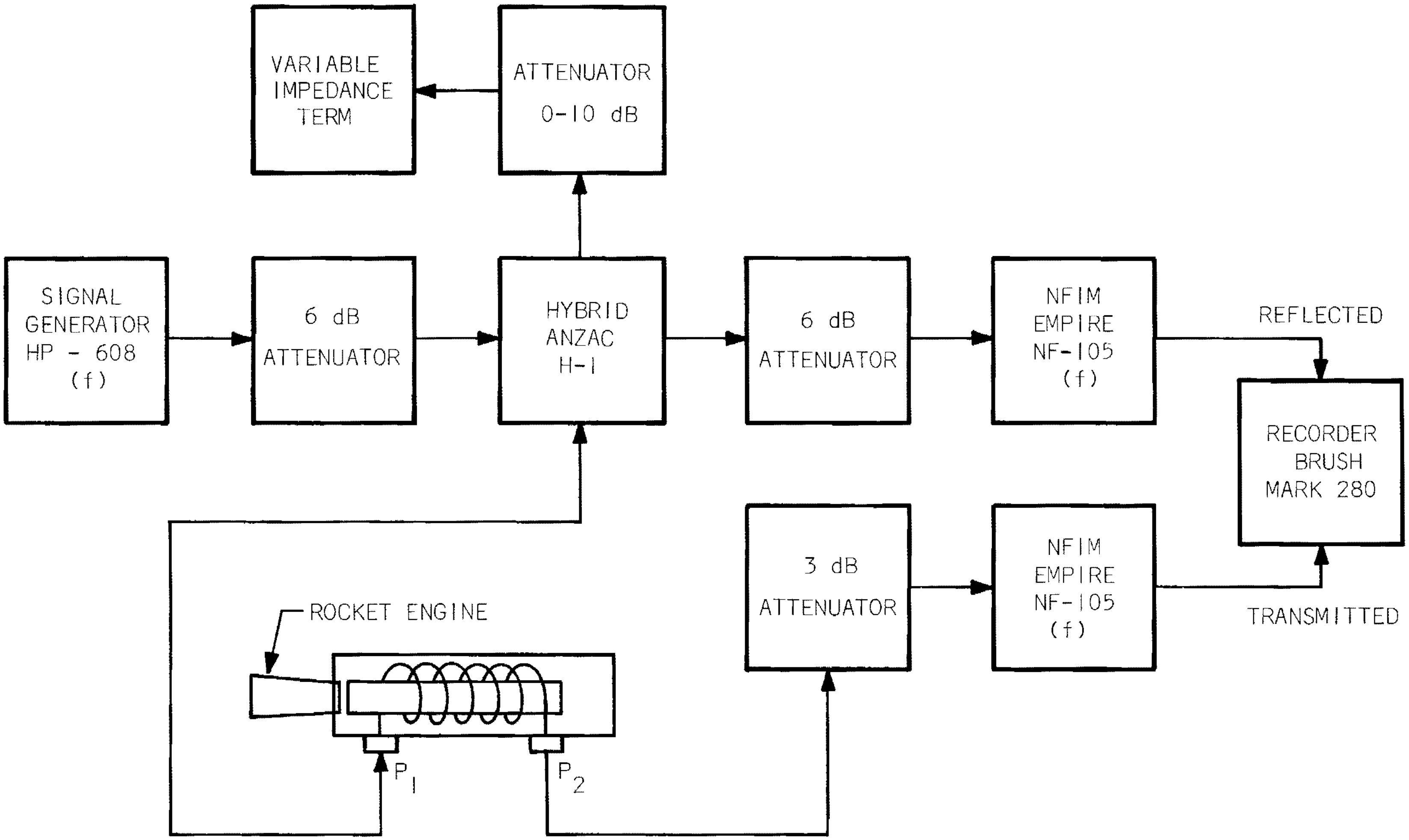

Figure 16. Test Setup for Power Transmission and Reflection Measurements.

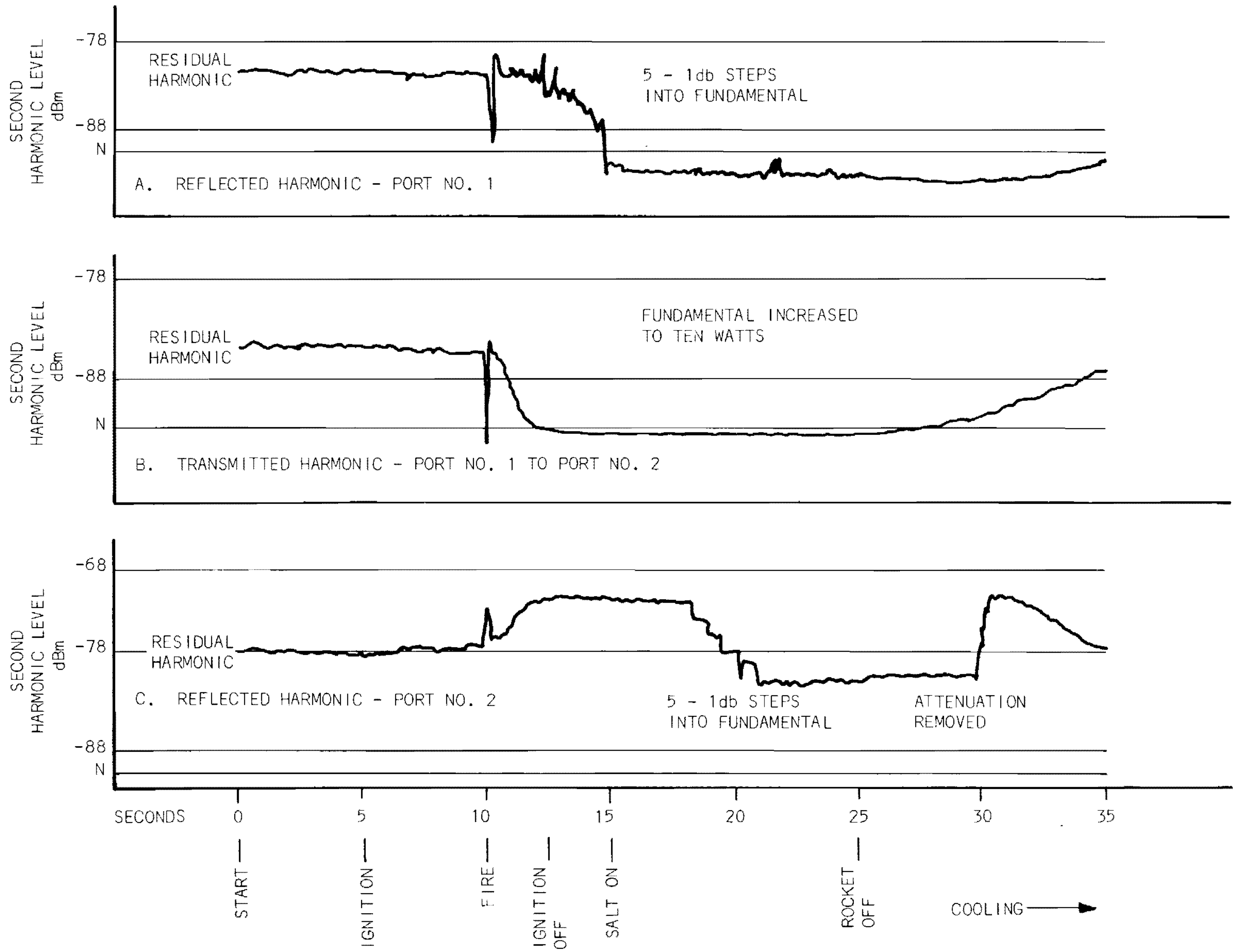

Figure 17. Second Harmonic Generation for Three Test Conditions Using a 220 MHz, 2 Watt Input Signal.

input levels of two watts because of equipment power limitations. Chart (a) in Figure 17 was obtained using a fresh silica liner in the helix which allows a clear indication of absorption at the instant the seeding compound is added to the flame. Charts (b) and (c) were made using the same liner, the salt residue from which seeded the flame as soon as it became hot, hiding any effect from the addition of seeding compound. In all three tests shown in Figure 17, the harmonic detection sensitivity was set to record the harmonic level leaking through from the generating equipment.

In the first two charts, the residual harmonic was only attenuated by the presence of the seeded flame. In the third chart, however, the harmonic reflected at port No. 2 rose some 6 dB upon reaching the ionization temperature of NaCl and a 2 for 1 harmonic level change was obtained for five 1 dB steps of attenuation of the fundamental level. The attenuation lowered the harmonic level some 4 dB below the original residual level emitted by the equipment. The engine was shut down after a 15 second run and allowed to cool, during which time the fundamental signal was returned to its original level. The harmonic level returned to that obtained while the engine was running and slowly fell to the original leakage level as the silica liner cooled below ionization temperature. The results of this test are not conclusive since no significant change in level was recorded when the engine was shut down. The maximum harmonic level fell to about 90 dB below the fundamental at the helix port (approximately 1/2 watt) which is not significant from an interference standpoint. This is the only instance in which a harmonic level larger than the residual was measured throughout the entire seeded flame test series. At the time the charts in Figure 17 were made, the degree of coupling afforded by the silica lined helix had not been ascertained. It was decided that the fundamental and harmonic levels should be recorded simultaneously for each test configuration and compared to equivalent recordings taken with a glow discharge tube inserted in the coupler. The charts shown in Figures 18 and 19 are typical of the results obtained from these tests. The small pip marks at the bottom of these and later charts indicate the occurrence of significant events in the testing sequence:

I = Ignition of Engine

F = Firing of Engine

I_{off} = Igniter off

S = Seeding on

OFF = Engine Shutdown

The time scale for all the strip charts made on the two channel recorder is one second per division.

In all cases tested, except as already noted, the second harmonic level was either attenuated or unaffected by the seeded flame plasma depending on the sensitivity of the initial detection level. The fundamental level was always attenuated as shown in the strip charts of transmitted levels. The reflected harmonic and fundamental levels behaved in a similar manner except that the reflected fundamental level did not drop more than a few dB when the seeding was initiated. The latter fact indicates that the helix was not well matched to the seeded flame plasma.

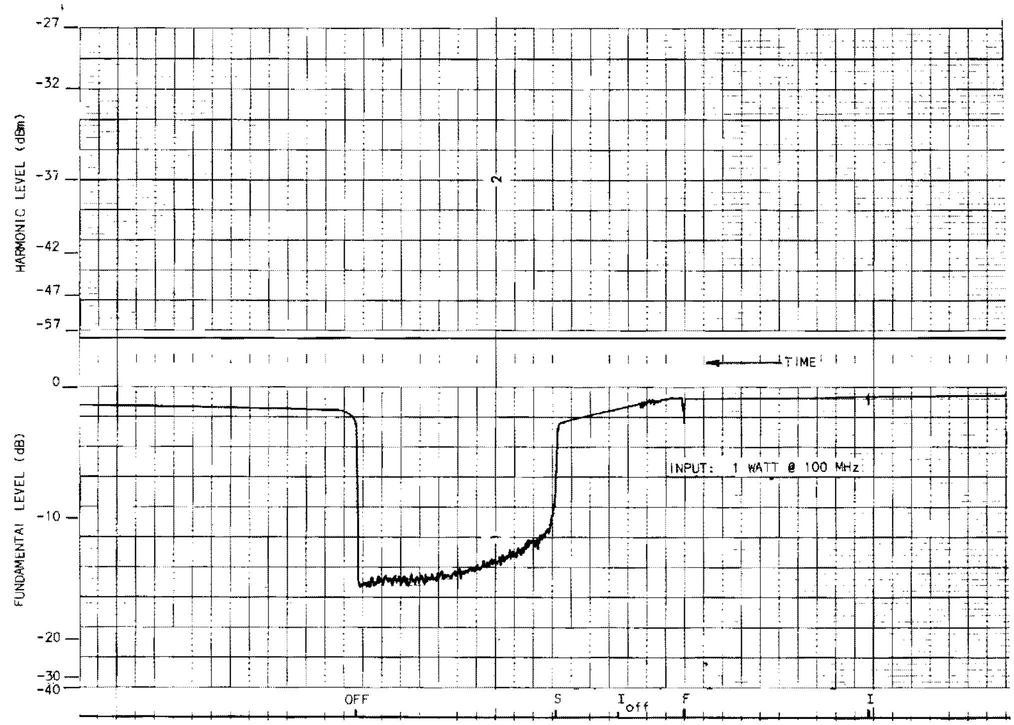

Figure 18. Transmitted Fundamental and Second Harmonic Levels for a Seeded Flame Plasma with One Watt Signal Input Level.

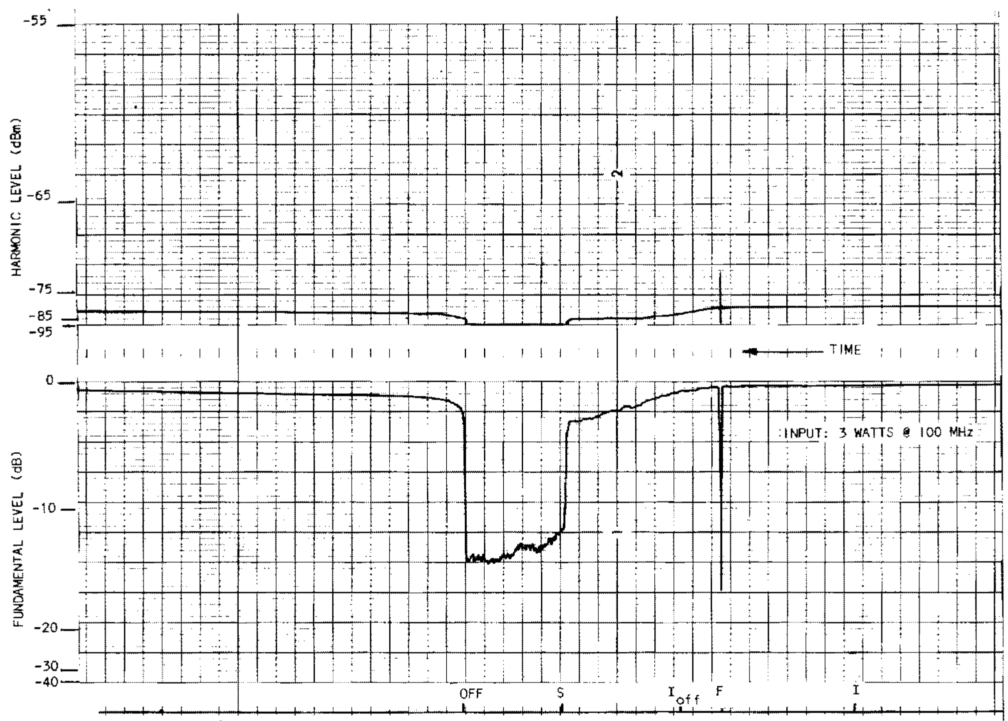

Figure 19. Transmitted Fundamental and Second Harmonic Levels for a Seeded Flame Plasma with Three Watt Signal Input Level.

The chart shown in Figure 20 was made at the same level of detection sensitivity as that shown in Figure 18 except that the small glow discharge tube was utilized rather than firing the engine. When the tube was triggered and sustained by a 60 Hz power source, a harmonic level of -39 dBm was obtained. When the 60 Hz source was removed, the 1 watt rf signal excited and sustained the plasma to produce a harmonic level of -31 dBm. Note that in both instances only a minute portion of the fundamental power was utilized in generating harmonics or sustaining the glow discharge (small fundamental loss).

Figure 21 is a chart showing the peak calibration of the measurement setup shown in Figure 16. When the chart was started (right) the hybrid was in place at port No. 1 of the coupler. At the first notation, the hybrid was removed from P_1 and the transmitted power fell to noise level. The reflected power level rose between 1 and 2 dB. At the second notation, the hybrid was terminated in 50 ohms which resulted in a minimum of reflected power. At the third notation, the termination was removed from the hybrid and at the fourth notation the hybrid was reconnected to P_1.

The charts shown in Figures 22 and 23 indicate the behavior of the reflected and transmitted fundamental power levels at ports P_1 and P_2 respectively for the seeded flame plasma (leads to ports switched in Figure 16). Those shown in Figures 24 and 25 indicate the same information for the small glow discharge tube. The chart in Figure 22 was obtained with a fresh silica tube while that in Figure 23 was obtained with the same tube once used. The effect of seeding is evident in both cases, though more activity is present in the latter chart during the period between firing (F)

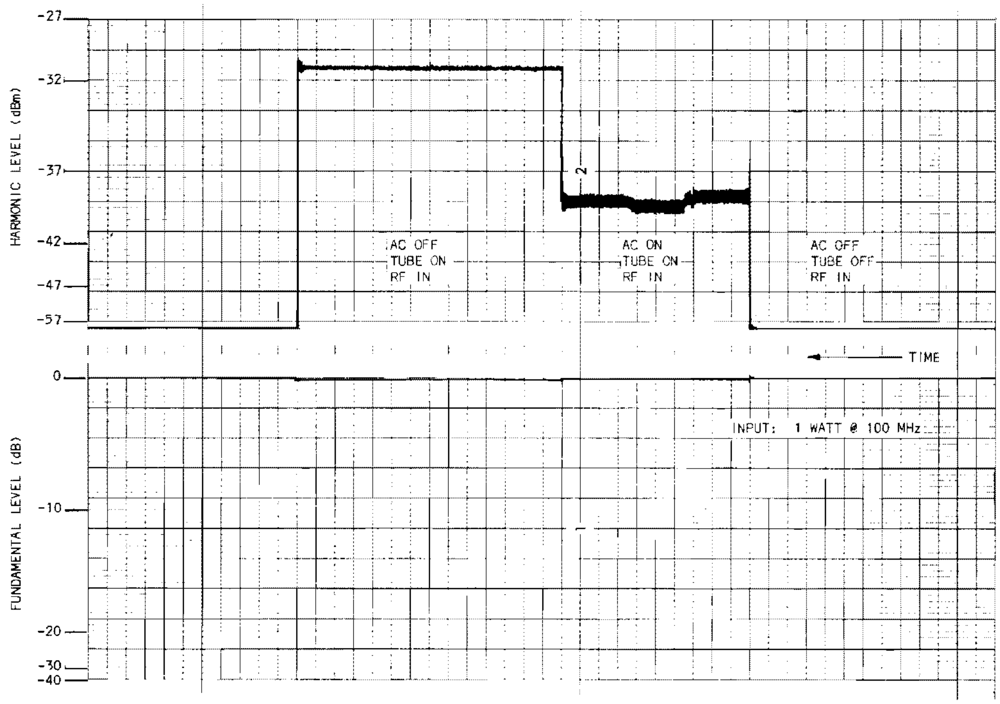

Figure 20. Transmitted Fundamental and Second Harmonic Levels for a Glow Discharge Tube.

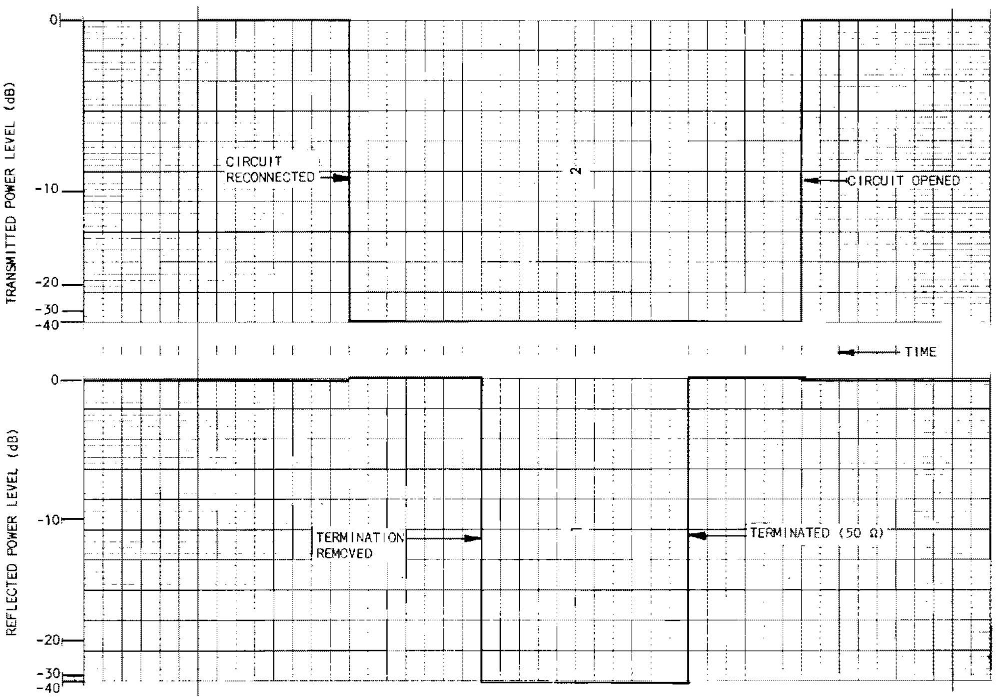

Figure 21. Peak Calibration of Setup for Measuring Transmitted and Reflected Power Levels.

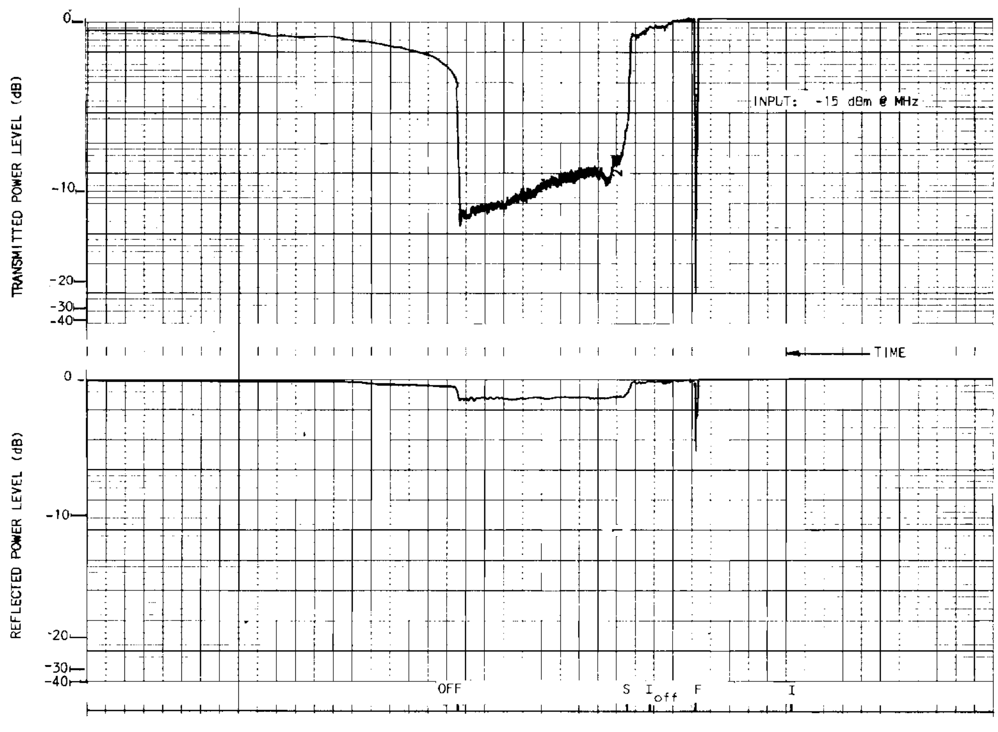

Figure 22. Power Transmission and Reflection at Port No. 1 for a Seeded Flame Plasma.

Figure 23. Power Transmission and Reflection at Port No. 2 for a Seeded Flame Plasma.

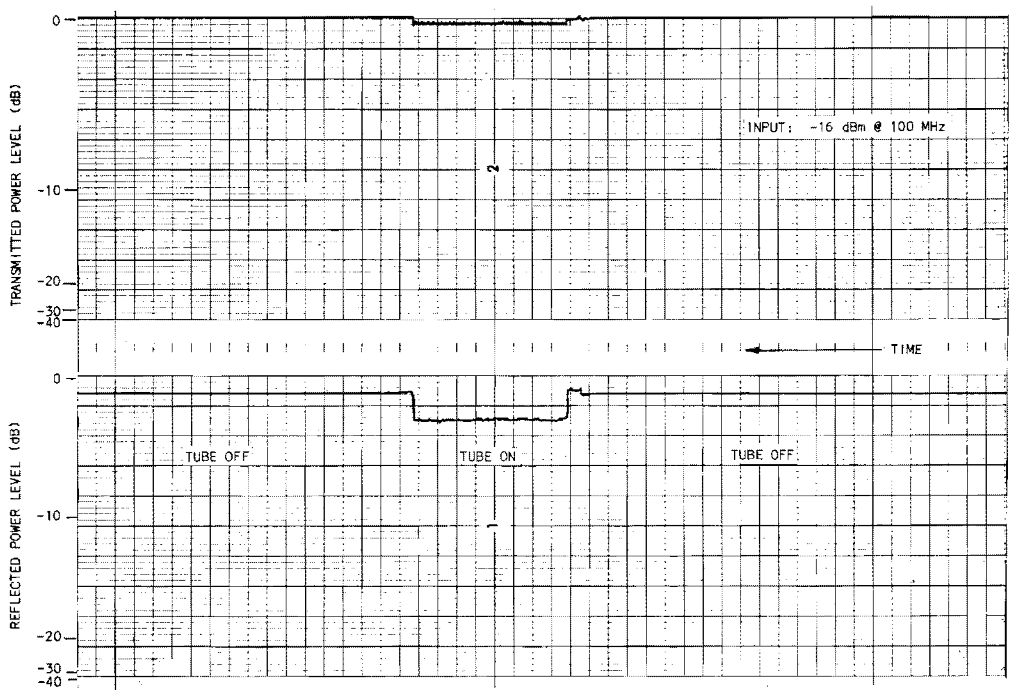

Figure 24. Power Transmission and Reflection at Port No. 1 for a Glow Discharge Tube.

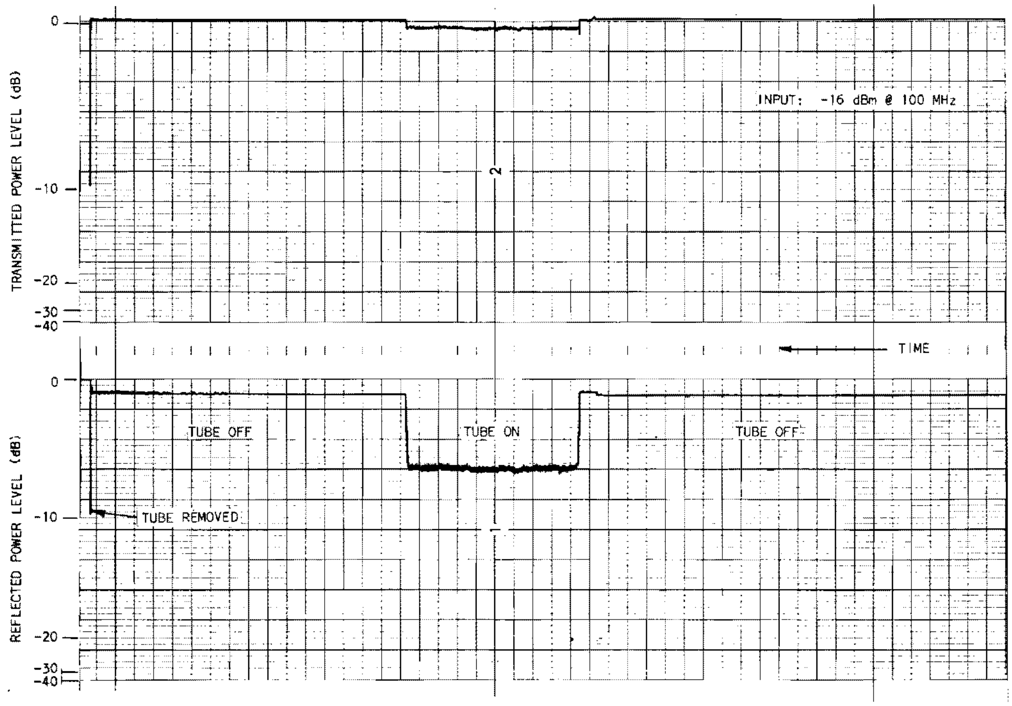

Figure 25. Power Transmission and Reflection at Port No. 2 for a Glow Discharge Tube.

and seeding (S). At the point marked "Recorder turned off" the chart drive was slowed by a factor of 100 for some 40 seconds to allow more cooling time to be shown. Poor but essentially equal signal coupling is indicated for both plasma media.

Calibration for these four tests was performed at the beginning of the series and spot checked at the end. A maximum drift error of 1 dB was obtained over the period of the four runs.

It is evident that the signal coupling for the small glow discharge tube was equal to or slightly better than that for the seeded flame plasma even though the latter was physically closer to the coupling helix. Under the essentially equal conditions of signal coupling, the seeded flame produced more than ten times as much attenuation to a transmitted signal as did the glow discharge tube yet no second harmonic of plasma origin could be detected for the seeded flame plasma. The seeded flame is obviously a much more lossy medium than the low pressure glow discharge. Under such conditions, any harmonic signal which might have been generated by the seeded flame would probably have been lost to absorption.

The extremely lossy nature of the flame plasma tested herein can be attributed to its relatively high pressure of operation. The estimated ratio of operating pressures for the flame and glow discharge plasma tested lies in the range between 10 and 30 to one. Energy loss in a plasma is a function of the electron-neutral particle collision frequency which is in turn a function of the absolute pressure. The measured difference in transmitted signal loss lies easily within the limits of the estimated pressure difference.

Power transfer to the plasma medium was better (closer match) at P_2 than at P_1 for both the seeded flame and the glow discharge. The transmission loss for signals propagating from P_2 to P_1 was also larger in both cases than that for signals propagating from P_1 to P_2. The difference in matching conditions at the two ports can be attributed to the pressure and temperature gradients along the flame column in the case of the seeded flame plasma and to the physical placement of the tube in the case of the glow discharge plasma. The difference in transmission loss with direction is not as easily explained but might be due to Faraday rotation phenomena enduced in the plasma by axial components of the earth's magnetic field.[9] The explanation is not entirely without plausibility because the rocket engine faces to the north such that the magnetic field could be axial.

Several tests of reflected and transmitted fundamental signal level were conducted using the setup shown in Figure 16 with seeding compounds other than sodium chloride. These tests are similar in appearance to those already shown and will only be described here.

Potassium carbonate seeding produced a slightly better match and a larger transmission loss than sodium chloride because it creates a higher electron density at the same temperature and pressure.[10] The dry nitrogen feed system, however, clogged repeatedly with the use of this material because of its large grain size and its hydroscopic nature. The minimal improvement in coupling characteristics afforded with this material did not warrant its further use.

Aluminum powder seeding produced lower reflected levels and a higher transmission loss than did either sodium chloride or potassium carbonate at the onset of seeding. This material, however, coated the silica liner with metallic and oxide deposits which rapidly reduced the coupling effectiveness of the helix. No further use was made of aluminum powder as a seeding agent.

C. Harmonic Studies Using Radiated Coupling Techniques on Glow Discharges

1. Radiated Tests - General

Radiated tests were conducted on low pressure glow discharge tubes arranged in two basic test configurations. One of these configurations was that of a plasma-metal dipole antenna and was designed to simulate an assumed rocket-body, rocket-exhaust dipole structure of a vehicle during launch. This configuration was tested both as a center fed dipole antenna and as an object of irradiation. The other configuration was a plasma slab built up of glow discharge tubes and provided a means for testing the nonlinear properties of large plasma sheaths. A description of both of these configurations is given in the Appendix.

One of the major problems encountered in performing the radiated tests resulted from the lack of an anechoic chamber which was entirely adequate. The lower frequency limit for the available chamber lies in the vicinity of 400 MHz whereas the dipole tests required a frequency range of 50-800 MHz. Thus all of the measurements recorded below approximately 400 MHz become suspect in that the reflection and absorption properties of the chamber are questionable. This problem makes the interpretation or correlation of measured data extremely difficult since the data probably reflect the characteristics of the chamber as well as the antenna system under test. The data are probably dependent upon the location of the test equipment within the chamber, and would be expected to vary as this location is changed.

It would have been highly desirable if plasma-metal dipole antennas could have been constructed whose tuned frequencies were well above the 400 MHz cutoff range of the anechoic chamber. Tests of harmonic generation and harmonic radiation versus frequency could have then been performed over a frequency range whose lower limit did not exceed 400 MHz. Such an antenna was not available, however, since glow discharge tubes were not available in such a small size.

Compounding the inadequacies of the anechoic chamber was the problem of exciting the glow discharge tubes without perturbing the environment within the chamber. Since dc supply or ac supply cables were required for the tubes, and since the rotation of the plasma test apparatus could not be made without movement of these cables, the antenna patterns recorded were to some extent a function of the cable location or movement during the tests. This problem was particularly predominant for the dipole tests which had to be performed at frequencies below 400 MHz.

A third difficulty experienced in the dipole tests was caused by leakage of the fundamental signal through the chamber walls during the harmonic measurements. Even though the test instrumentation was tuned to the second harmonic frequency, the pattern recorder was extremely susceptible to the large residual fundamental signal level. In some cases, the effect of this residual level was of the same order of magnitude as the harmonic level, making harmonic patterns difficult to record.

2. Plasma-Metal Dipole Studies

Two basic tests, distinguished as center fed or double radiated tests, were conducted on the plasma-metal dipole antennas in an anechoic chamber whose approximate dimensions are 12 x 12 x 12 ft. In the first of these tests, the dipole was connected as a center fed transmitting antenna and radiation patterns of fundamental and harmonic signal levels were recorded using the test setup of Figure 26. Patterns were recorded in 10 MHz steps for fundamental input frequencies ranging from 50 MHz to 800 MHz. For each measurement, the power amplifier was adjusted for an output of 10 volts, and the receiving antenna was tuned to the proper frequency. For tests on the 220 MHz antenna using 8 watt glow discharge tubes, the tube current was adjusted to 150 ma. Tube current for the 6 watt tubes in the 290 MHz antenna was set to 130 ma.

Polar radiation patterns for both the fundamental and the second harmonic are shown for four representative receiving frequencies in Figure 27. The plasma arm of the dipole lies in the direction of 270 degrees for these patterns. In general the patterns for the fundamental signal approximate those for a broad element, fixed length metal dipole. At the higher frequencies, plasma absorption seems to diminish the strength of fundamental radiation in the hemisphere containing the plasma arm.

The harmonic pattern is plotted in dashed lines directly on the fundamental pattern for the same radiated signal frequency. These patterns were made to determine whether or not there is any similarity between the radiation patterns of two signals of identical frequency one of which is fed directly to the dipole from a signal generator and the other of which is

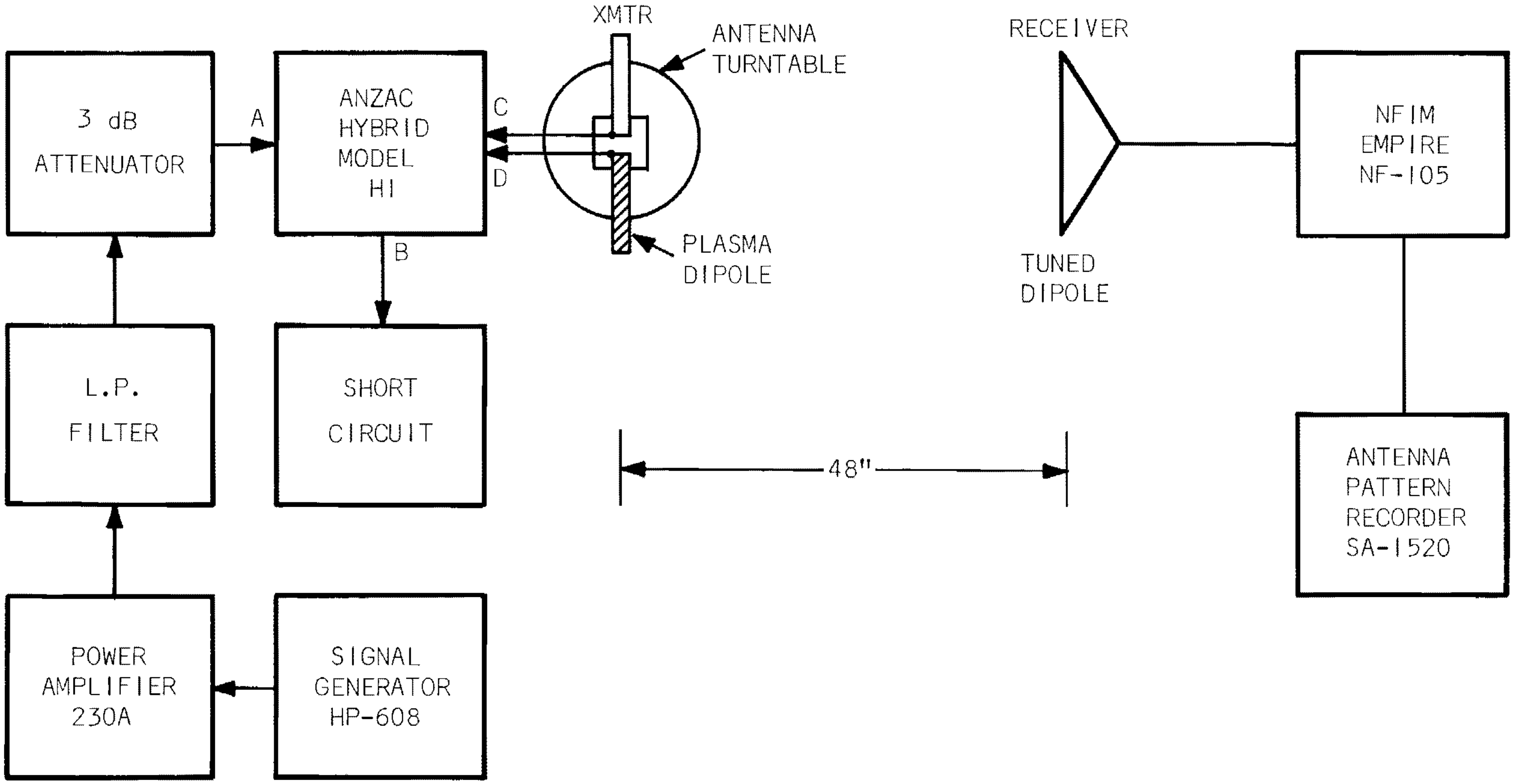

Figure 26. Test Setup for Center Fed Plasma-Metal Dipole Tests.

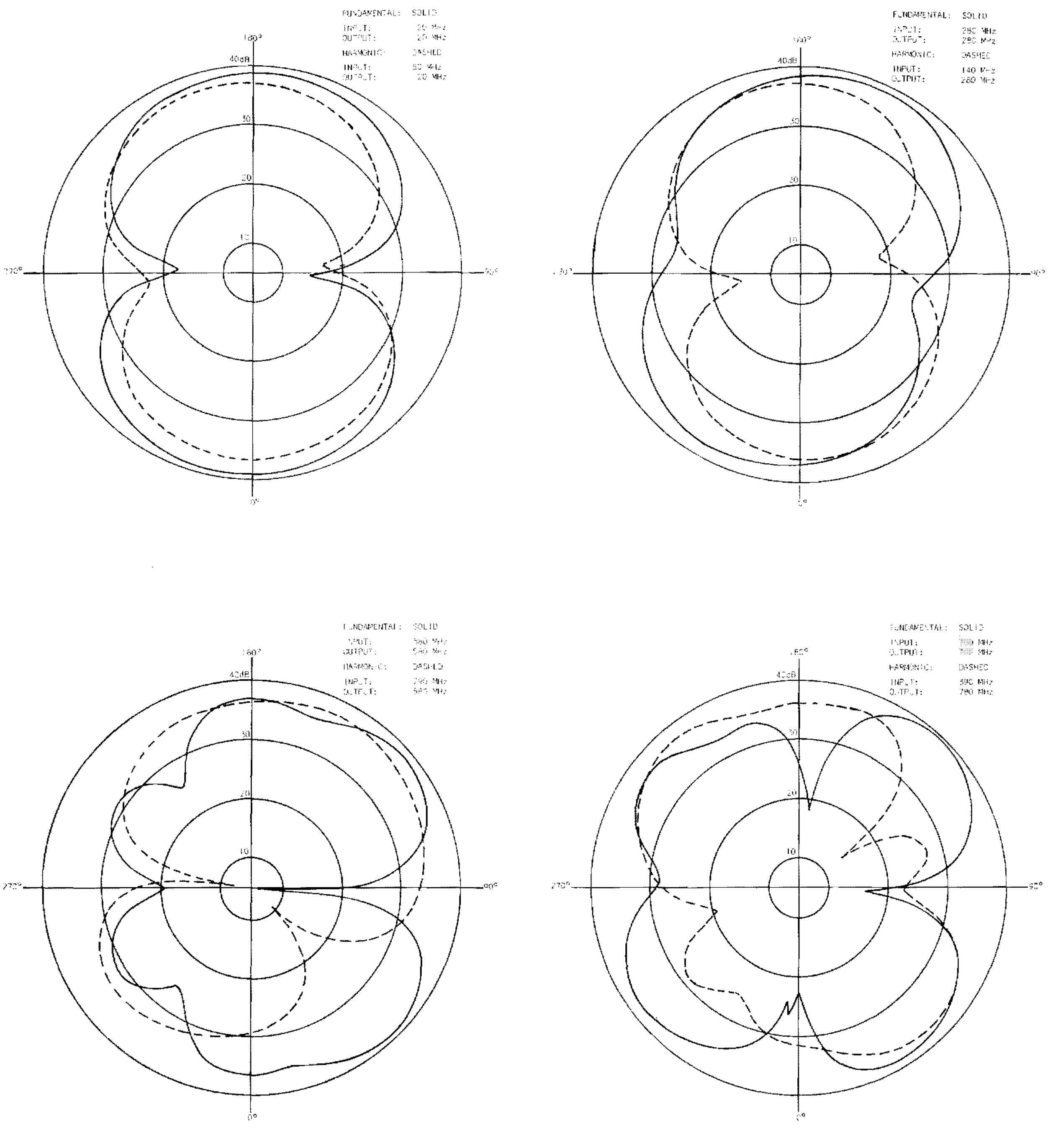

Figure 27. Harmonic and Fundamental Patterns for a 220 MHz Plasma-Metal Half Wave Dipole Using a Center Fed Technique.

generated within the plasma by driving the plasma at the subharmonic frequency. For frequencies below dipole resonance to frequencies of about double dipole resonance the patterns for these tests are reasonably similar. Above some 480 MHz, however, the generated harmonic pattern deviates severely from the fundamental pattern. The deviation at high frequencies may be due largely to the differences in effective feed configuration with the center fed setup. The fundamental is fed to the antenna in a truly balanced condition, i.e., the plasma and metal arm are fed equally and oppositely phased. The harmonic signal, being generated only in the plasma arm, cannot possibly maintain a balance feed condition over the entire frequency range because of the travel time and loss through the balun and associated cabling.

Prior to the plasma tests, a two dipole coupling characteristic was run using tuned dipoles of the Empire 105 series. The tuned dipole characteristic was obtained to establish coupling conditions within the room for use in normalizing the plasma data. The fundamental coupling characteristic is shown as a function of frequency for the tuned dipoles and both plasma dipoles in Figure 28. The peak pattern values for the plasma dipoles were used to plot their characteristics to avoid nulls in the radiation patterns associated with these antennas. The chamber used for these tests is obviously not anechoic below about 400 MHz nor is it rated to be. The data, however, are felt to be correctable to a large extent.

Figure 29 is a comparison on a fundamental frequency basis of the measured second harmonic levels radiated by the two test plasma-metal

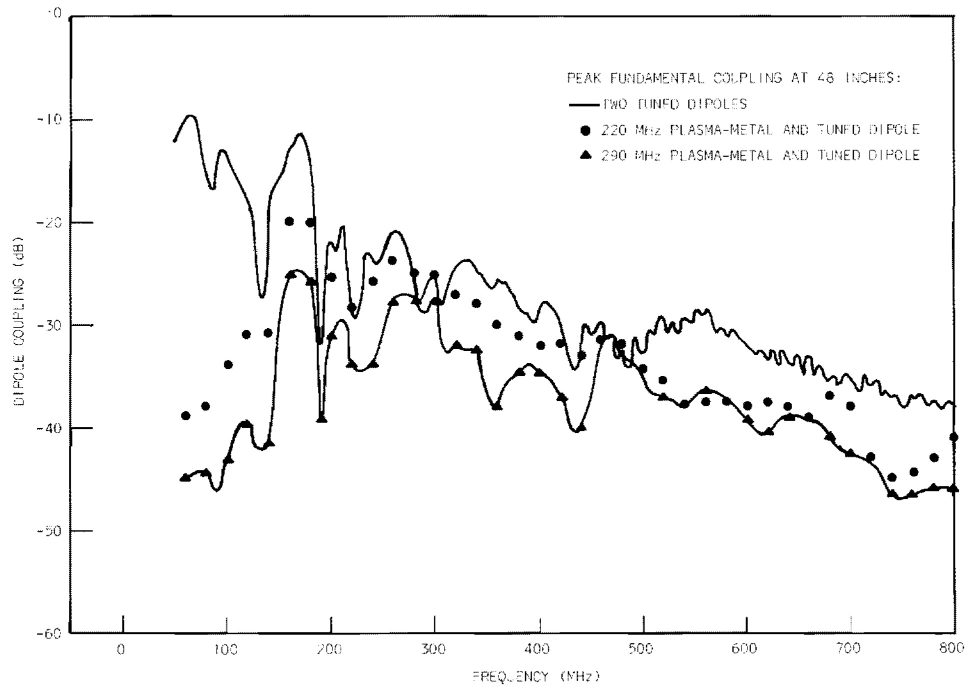

Figure 28. Antenna Coupling as a Function of Frequency Under Center Fed Conditions.

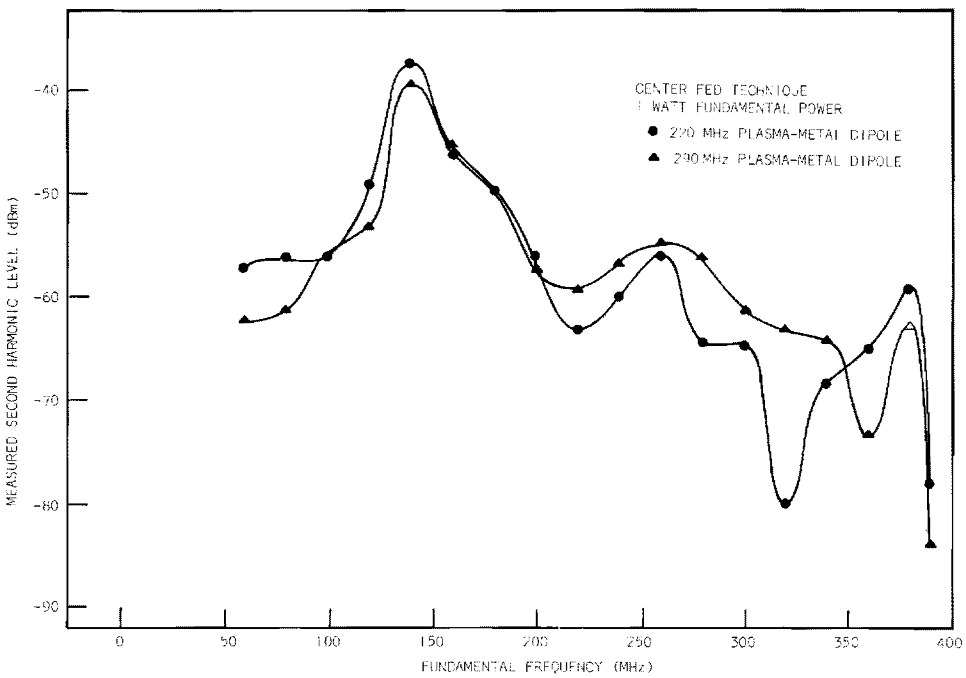

Figure 29. Measured Second Harmonic Level as a Function of Fundamental Frequency - Center Fed.

dipole antennas center fed with a one watt power level. The actual frequency at which the harmonic levels were measured is obtained by doubling the frequency shown on the abscissa. The data show little evidence of antenna resonance effects either at the fundamental or the harmonic frequency in the uncorrected state, because the evidence sought is swamped by chamber reflection peaks, resonance effects of the plasma medium proper, and matching variations in the center feed mechanism. Most of these effects are obviously common to both antennas on a frequency basis.

When the data for the two antennas are compared on the basis of antenna length in electrical degrees, the effects common to frequency can be averaged to give a smooth curve of the harmonic level as a function of the length of the plasma column. The bold smooth curve in Figure 30 is a graphical average of the harmonic data for the two antennas and shows a definite peak at about 45 degrees. The peak coincides with the first antenna resonance (90 degrees) at the harmonic or radiated frequency for the antennas under test. There is no evidence of increased harmonic generation due to antenna resonance at the fundamental frequency.

The peak of harmonic level at the antenna resonance length is due largely to the improved radiating characteristics of an antenna at this length. The radiating efficiency and room variation can be effectively removed from the data by normalizing it to the fundamental coupling data previously measured for the two dipoles. The individual antenna curves shown in Figure 31 have been corrected for coupling and room variations by normalizing to the corresponding coupling data shown in Figure 28. The bold smooth curve is again a graphical average of the data for the two

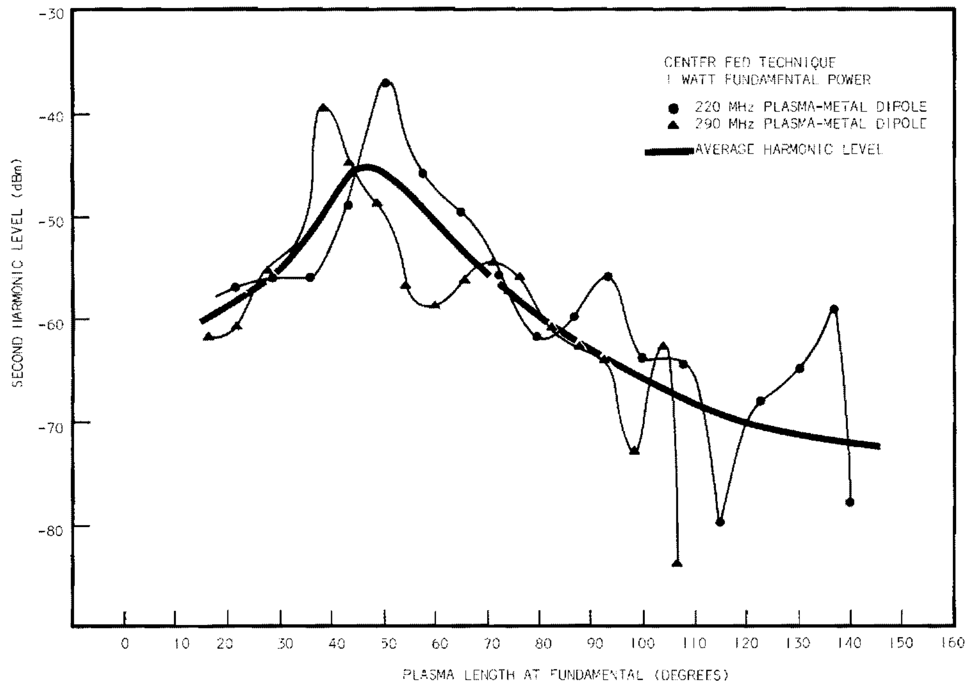

Figure 30. Measured Second Harmonic Level as a Function of Plasma Length - Center Fed.

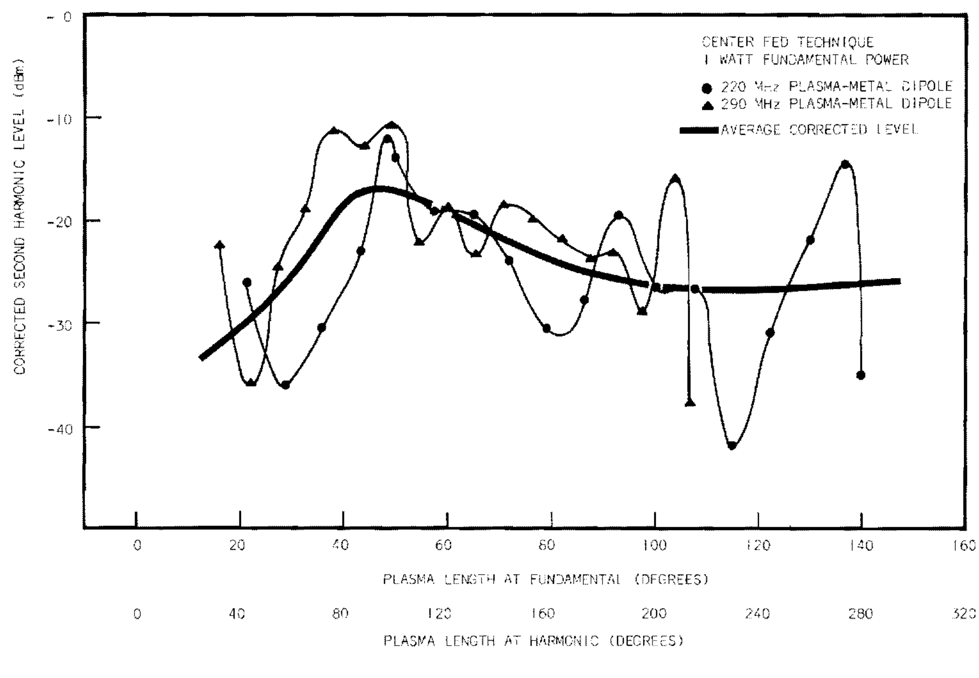

Figure 31. Second Harmonic Levels Corrected by Measured Coupling Loss to Receiving Dipole as Determined by Center Fed Measurement.

antennas. Again there is no evidence of improved harmonic generation because of antenna resonance at the fundamental frequency. At the harmonic frequency, however, there remains a small peak near the first antenna resonance. This may be indicative of a reactive type of nonlinearity which can be enhanced by resonance conditions at the harmonic frequency.

The second basic plasma-metal dipole test was conducted using the test setup of Figure 32. Here the plasma-metal dipole was placed directly between a transmitting and receiving antenna, and harmonic levels were measured as a function of the plasma dipole antenna rotation. Patterns were again recorded in 10 MHz increments for fundamental frequencies from 50 MHz to 800 MHz, for the same power amplifier voltage and tube excitation conditions noted above.

Polar radiation patterns of the second harmonic signal are shown for twelve representative frequencies in Figures 33, 34, and 35. The plasma arm of the dipole lies in the direction of 270 degrees for these patterns which are oriented with respect to the receiving rather than the transmitting probe antenna. The patterns resemble those of a metallic dipole antenna with a narrowed beamwidth when considered with respect to the fundamental frequency. The overall pattern is a convolution of the pattern at the fundamental and that at the harmonic for each test frequency. Had time permitted, patterns of the double radiated type would have been made for a 90 degree orientation of the two test antennas as well as the 180 degree position.

The antenna patterns alone indicate that the harmonic generation in the plasma is strongly related to the antenna's acceptance of the fundamental

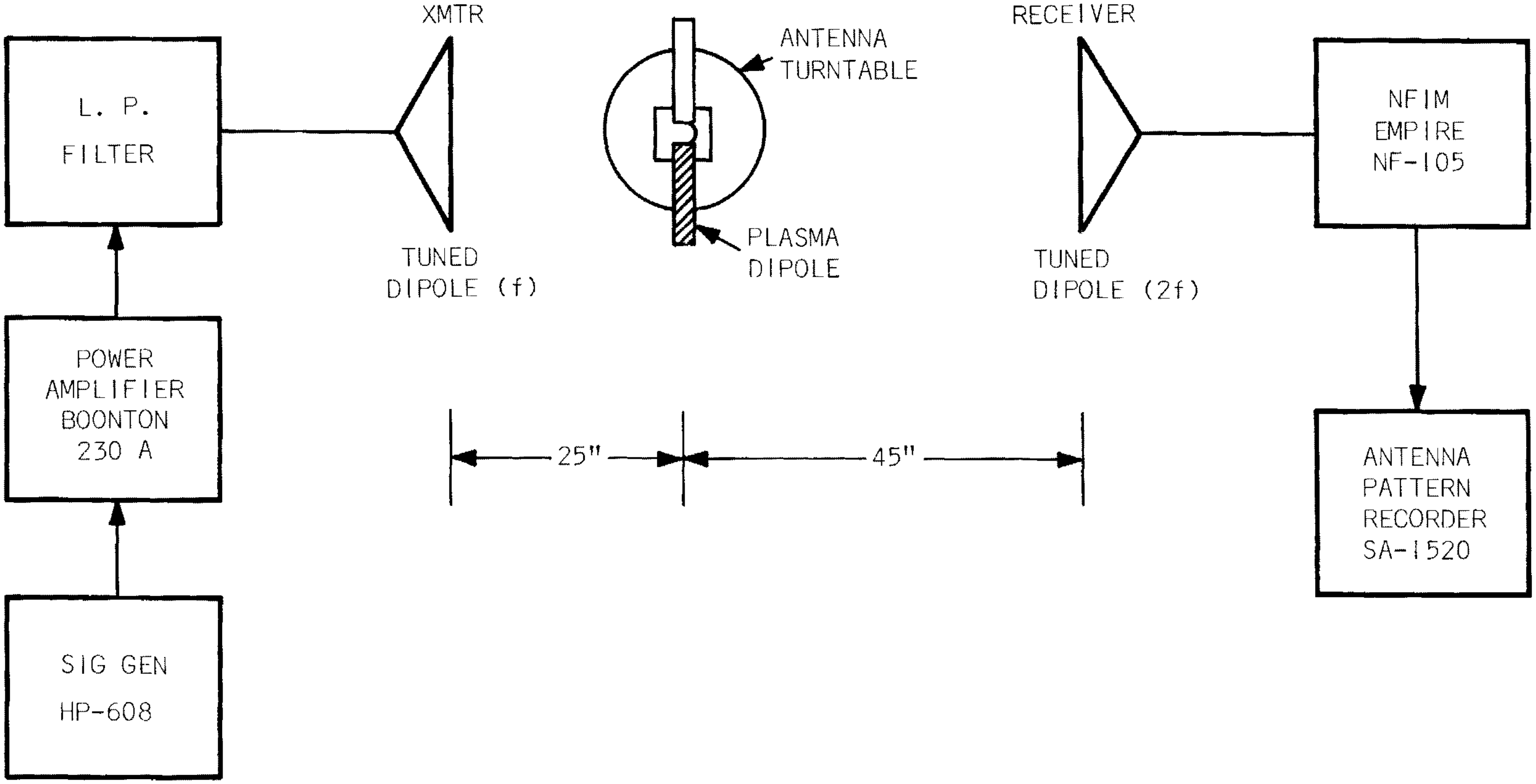

Figure 32. Test Setup for Double Radiated Tests of Plasma-Metal Dipole Antennas.

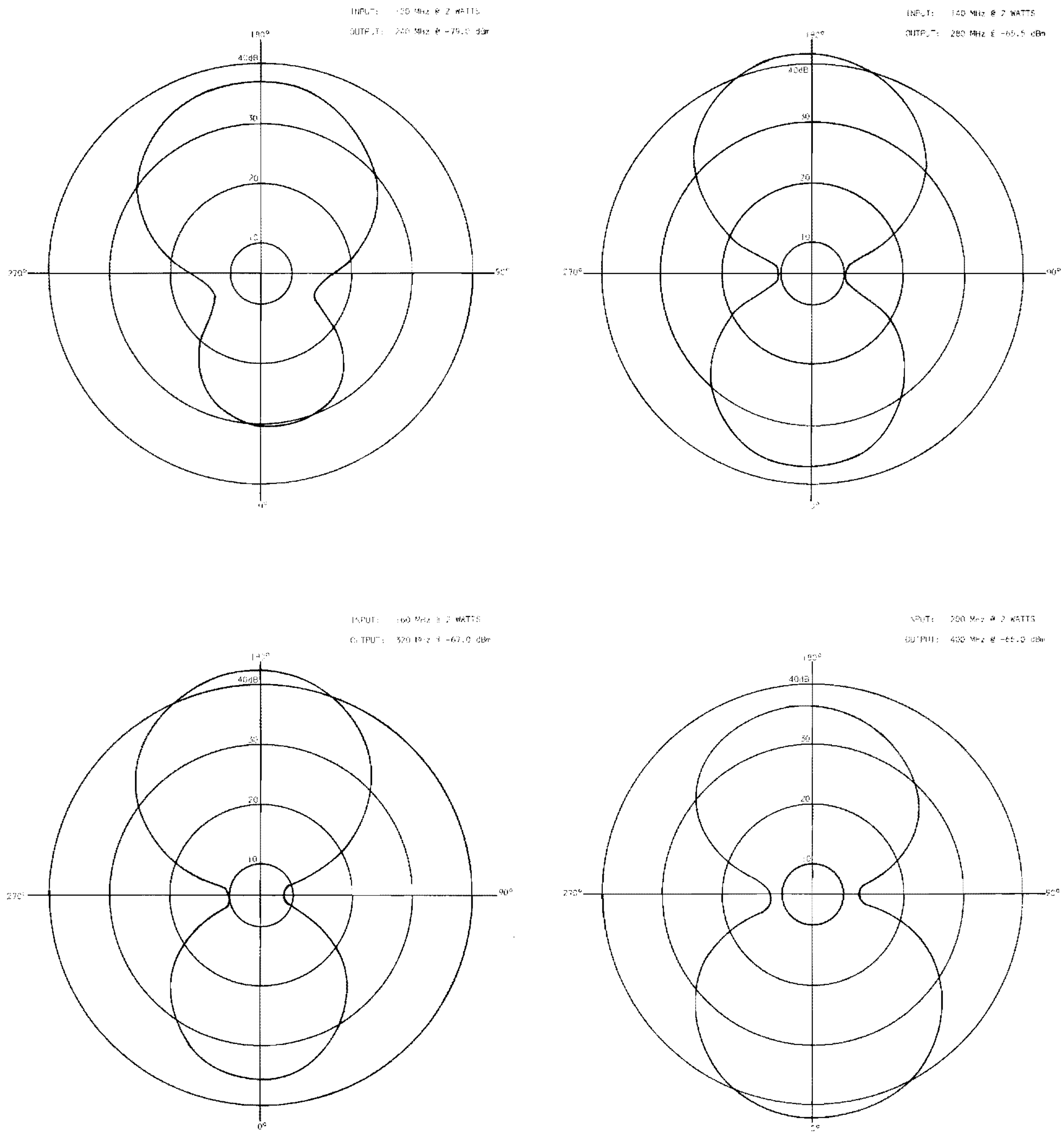

Figure 33. Harmonic Patterns for a 290 MHz Plasma-Metal Half Wave Dipole Using the Double Radiated Technique Below Resonance.

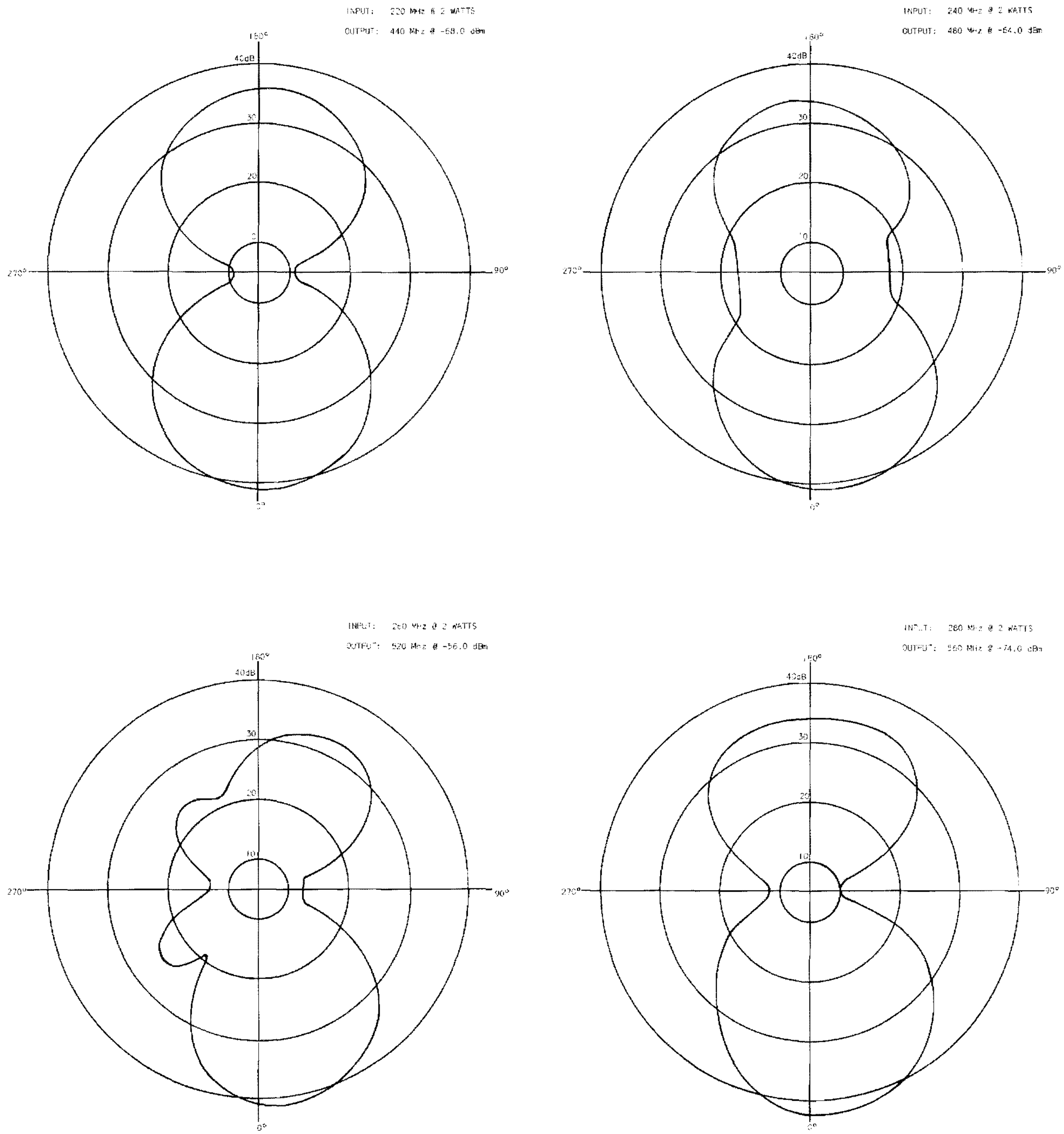

Figure 34. Harmonic Patterns for a 290 MHz Plasma-Metal Half Wave Dipole Using the Double Radiated Technique Near Resonance.

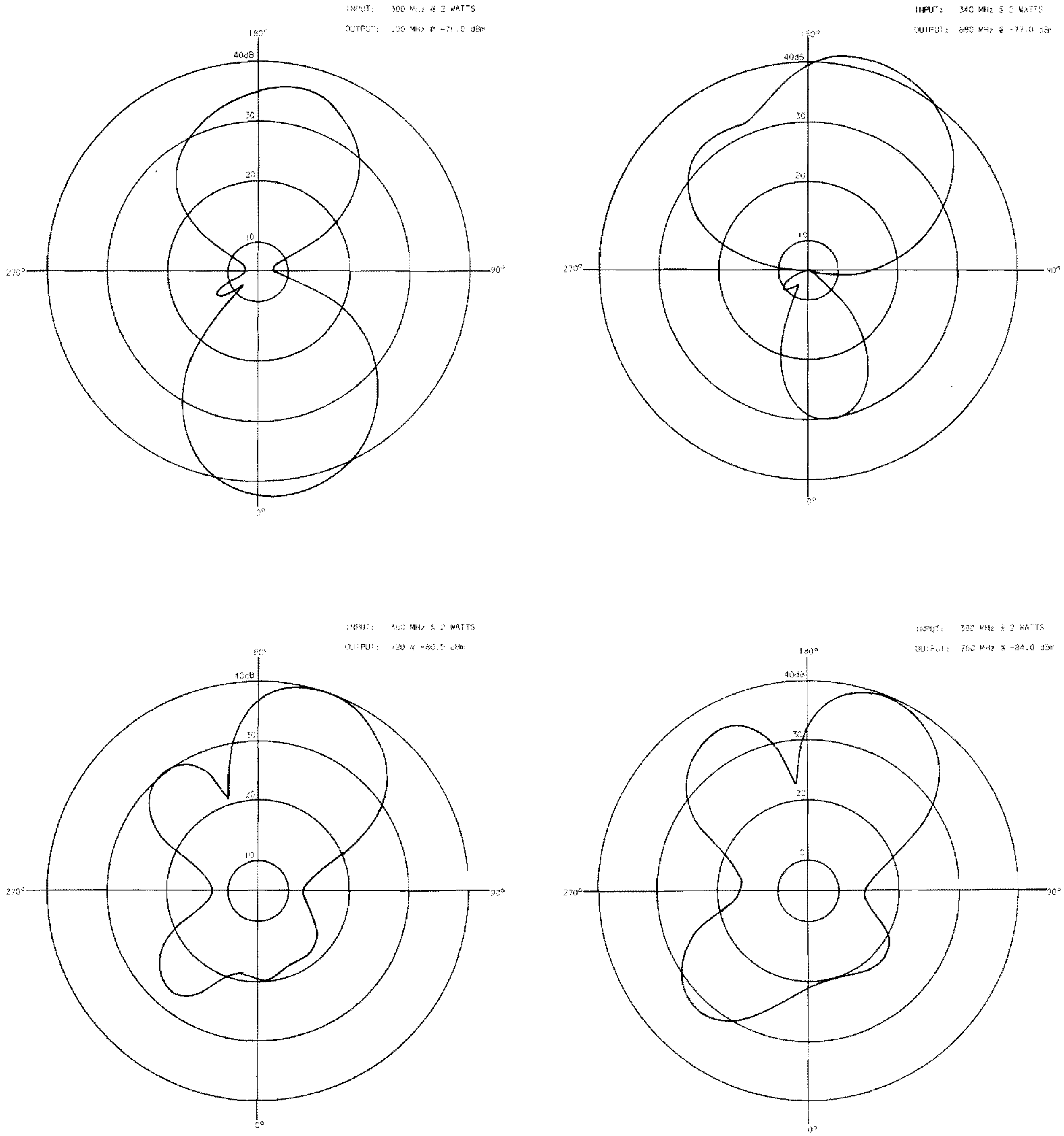

Figure 35. Harmonic Patterns for a 290 MHz Plasma-Metal Half Wave Dipole Using the Double Radiated Technique Above Resonance.

signal. The dependence with respect to the fundamental signal is further exemplified by the plots of measured level shown with respect to frequency in Figure 36. These are the peak levels taken from the patterns for the two antennas without correction. At the highest point, the radiation level at the second harmonic is equivalent to -25 dBm into a tuned dipole. Chamber effects and other resonances common to the measurement system are exemplified in the comparison of these two curves plotted on the basis of frequency.

An excellent example of the effect of antenna resonance at the fundamental on the level of second harmonic which can be measured at the terminals of a probe antenna is shown in Figure 37. The peak of activity under these conditions occurrs between 60 and 70 degrees of plasma length. The 60 to 70 degree peak is actually somewhat below the normal resonance point because the coupling characteristics in the chamber tend to bias the data. Two bases of correction were applied to the measured data with essentially equal results.

The curves shown in Figure 38 are corrected for cable loss and the radiating characteristics of the two probe antennas only. This establishes a curve of the peak radiated level as a function of the length of the plasma column relative to the fundamental frequency. The shape of this curve is quite similar to that representing the level of second harmonic generated within the plasma column as a function of plasma length at the fundamental. The latter curve is shown in Figure 39 and was arrived at by correcting the measured data for cable loss, the transmitting dipole characteristics, and the measured coupling loss to the receiving dipole as shown in Figure 28.

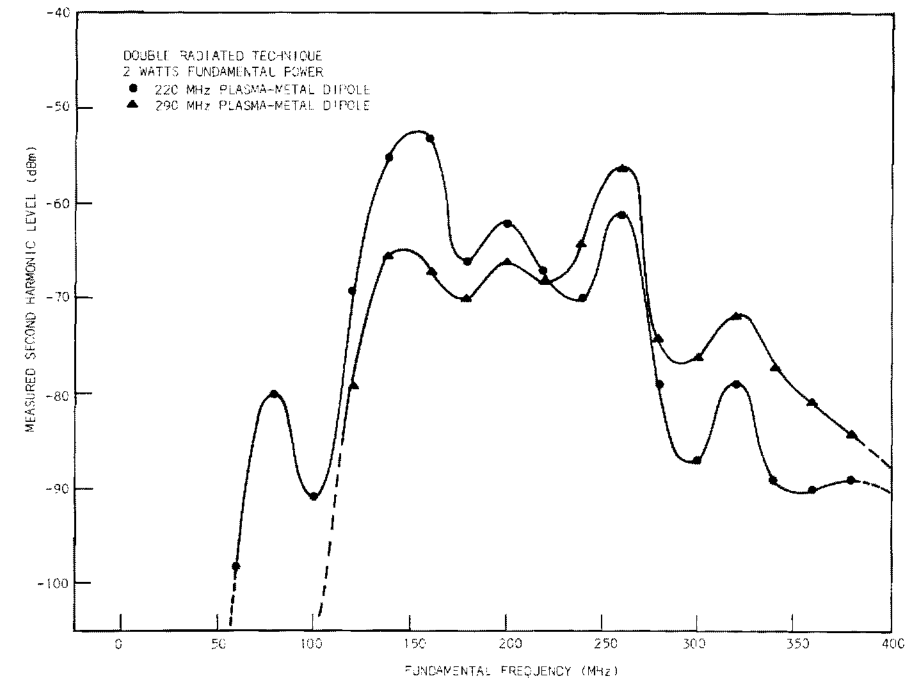

Figure 36. Measured Second Harmonic Level as a Function of Fundamental Frequency - Double Radiated.

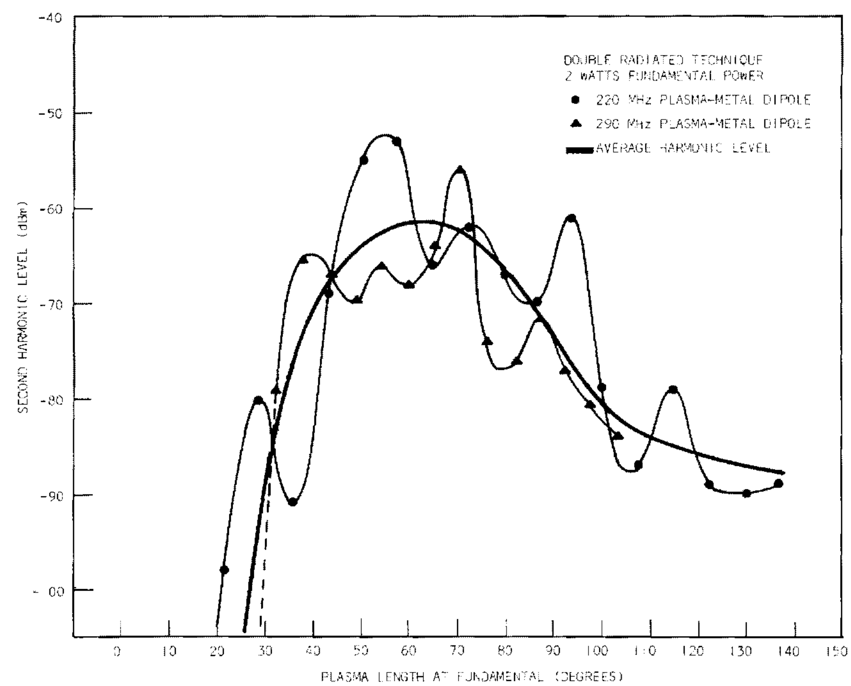

Figure 37. Measured Second Harmonic Level as a Function of Plasma Length - Double Radiated.

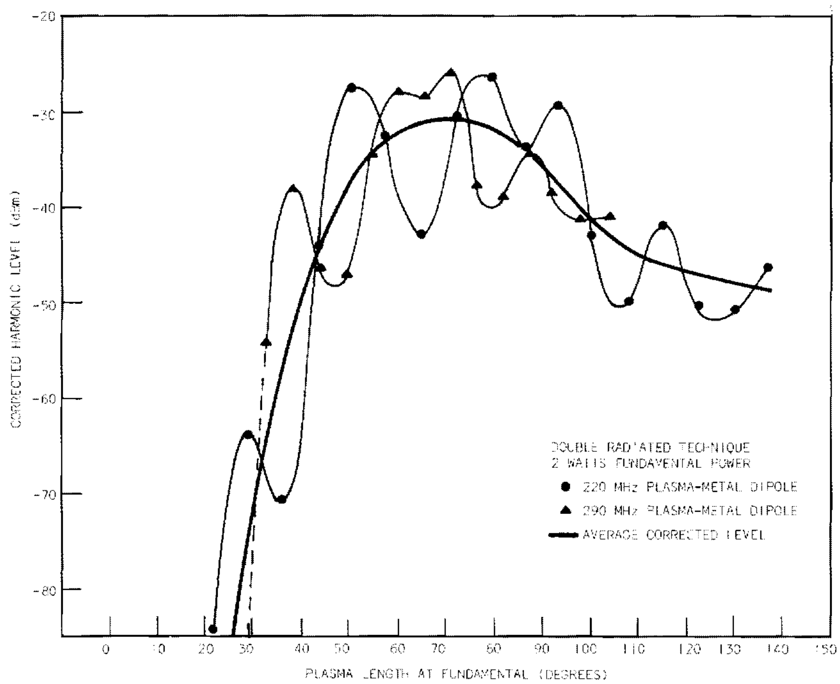

Figure 38. Harmonic Levels Corrected by Tuned Dipole Coupling Characteristics.

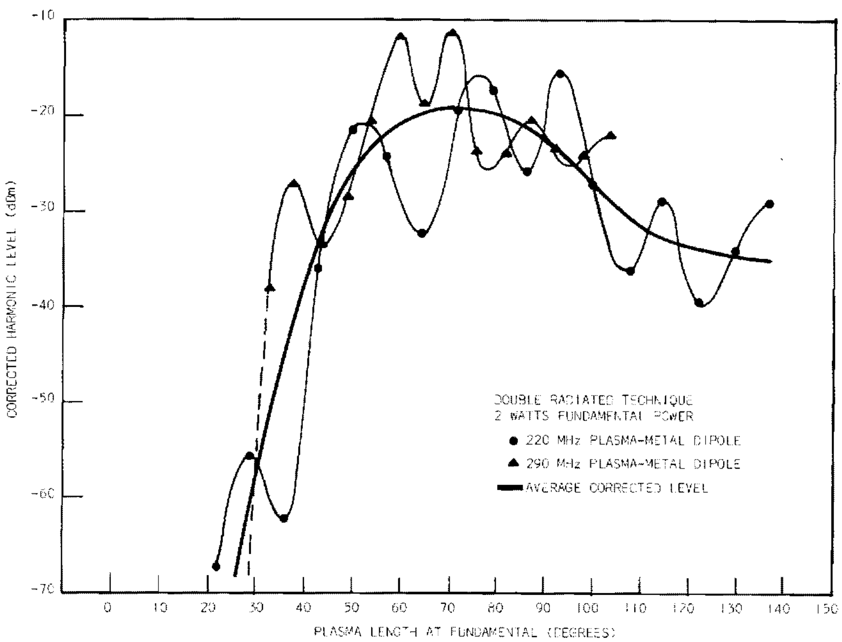

Figure 39. Second Harmonic Levels Corrected by Transmitting Tuned Dipole Coupling Characteristic and Measured Coupling Loss to Receiving Dipole as Determined by Center Fed Technique.

The peak generated levels shown in Figure 39 agree quite favorably with the levels measured using the coaxial coupler as presented in Section A of this chapter and with the peak levels shown in Figure 31 of this section.

Figure 40 is a comparison of the center fed and the double radiated data. The center fed data were presumed flat and the double radiated data were normalized thereto. This curve provides perhaps the best indication of the effect of macroscopic plasma resonance on the harmonic level produced by irradiation at the fundamental frequency. At best, radiated electromagnetic coupling is not as effective as conducted electromagnetic coupling. However, at the peak of radiated coupling, the difference amounts to only a 3 to 4 dB loss in fundamental using the radiated technique.

The graphically averaged data shown in this section indicate that the peak in fundamental coupling occurrs for a plasma length of some 70 degrees. Considering that waves travel more slowly on the plasma than on metal, 70 degrees corresponds well to the 80 degrees for metallic dipole resonance. The graphical averages given here were checked by two separate arithmetic averaging techniques which yielded essentially equivalent results for the resonant length of the plasma column.

3. Composite Plasma Slab Studies

Tests on the plasma slab were performed using the test setup shown in Figure 41. The slab was subjected to an incident 400 MHz electromagnetic wave and the second harmonic level generated in the plasma was measured as the slab was rotated through 360 degrees. This measurement was conducted for the four angular positions of the receiving antenna shown in

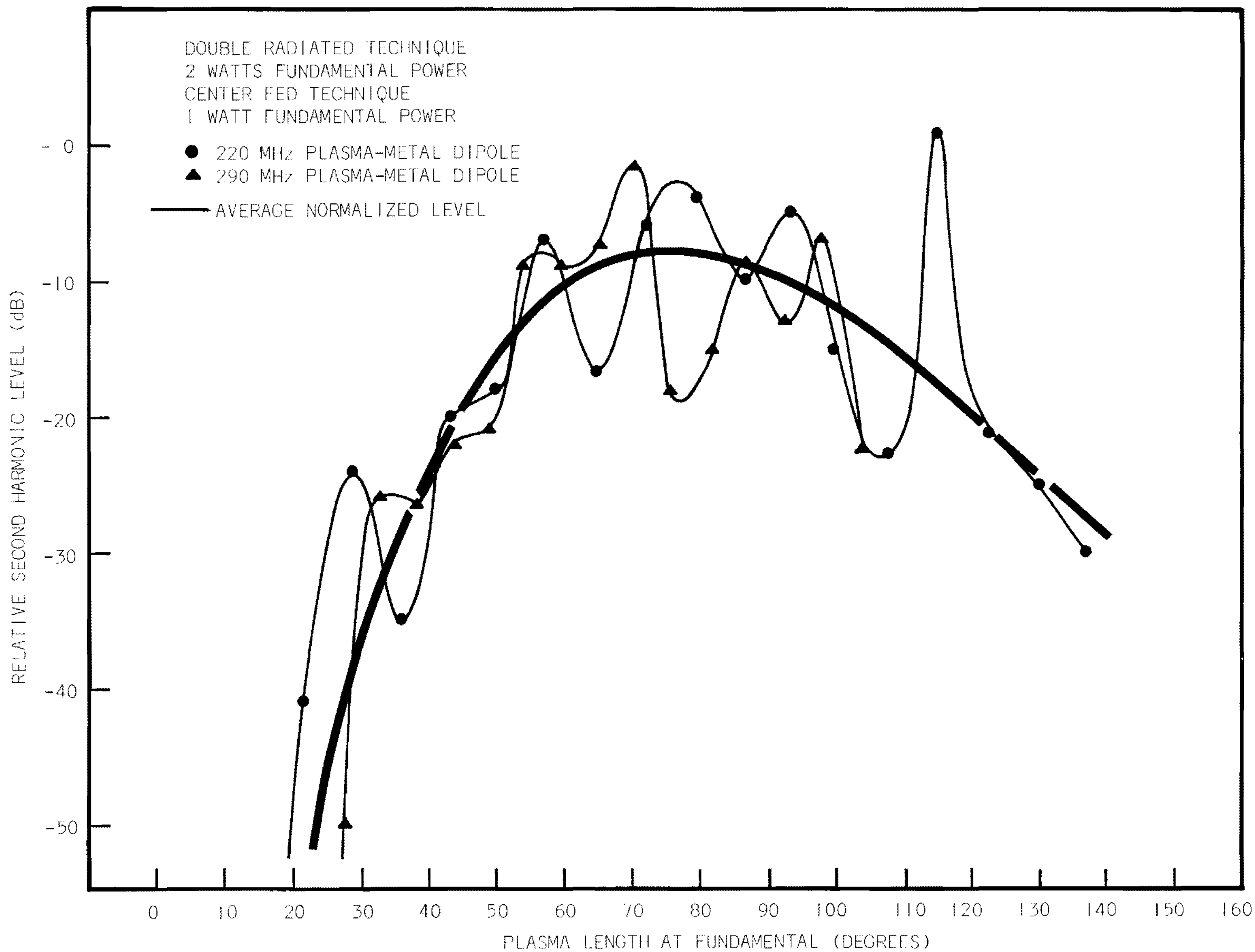

Figure 40. Second Harmonic Level from Double Radiated System Relative to Second Harmonic from Center Fed System (0 dB).

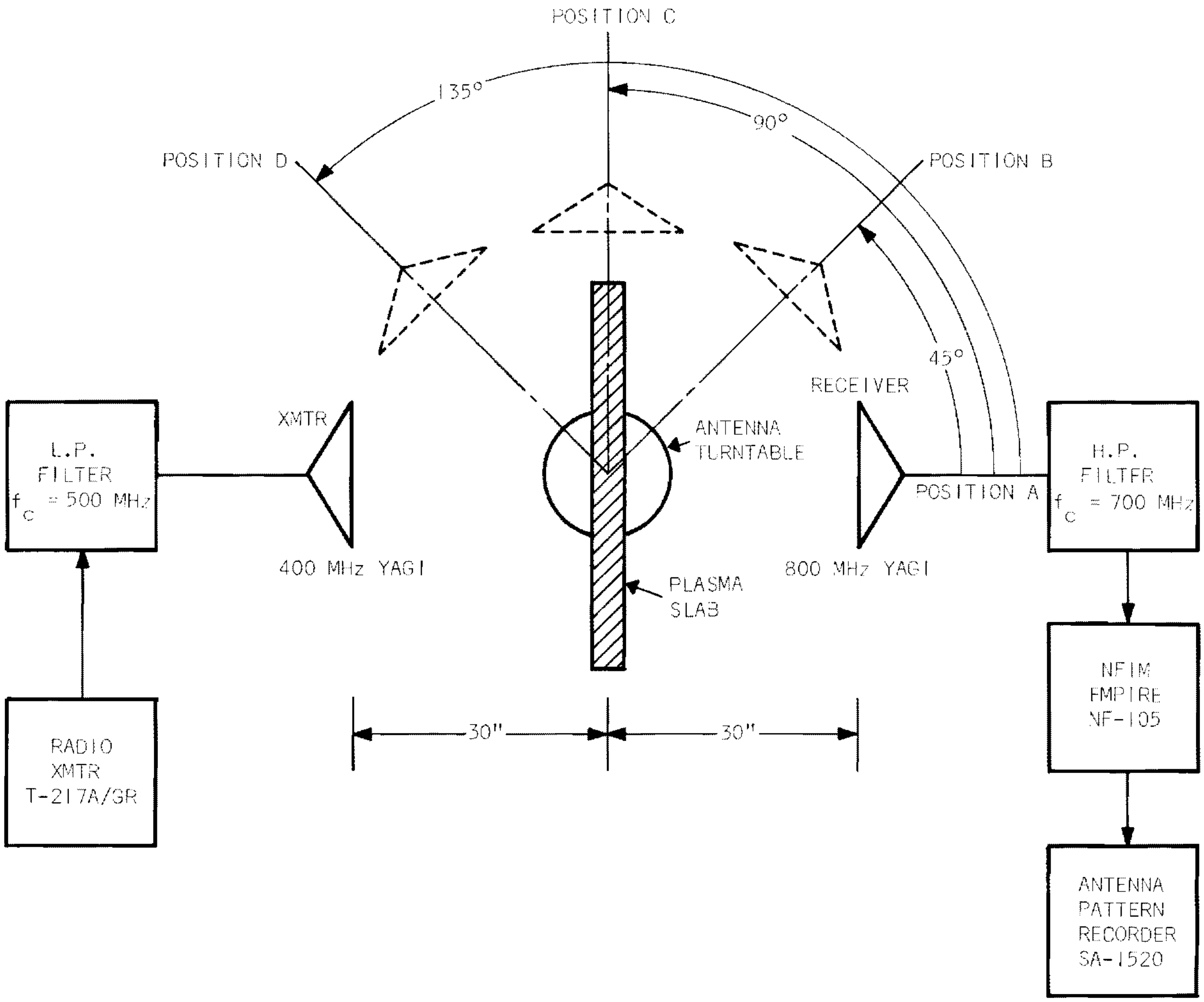

Figure 41. Test Setup for Radiated Tests of Plasma Slab.

Figure 41, as well as for all combinations of vertical and horizontal polarization positions of the transmitting and receiving antennas. The effective input power to the transmitting antenna was approximately 118 watts for all high level tests, with a VSWR at the transmitter output of less than 1.1. All of the glow discharge tubes in the slab were energized during the tests with an ac voltage of approximately 100 volts at the ballast primaries. In order to compare these tests to those using the plasma metal dipoles, one set of measurements was made using tuned dipole antennas at both 2 and 118 watt signal levels. The remaining tests were performed using the tuned Yagi antennas described in the Appendix.

Figures 42 through 45 show the patterns obtained with the Yagi antennas and a 118 watt fundamental signal. The patterns include a full 360 degrees with clockwise rotation proceeding from right to left across the pattern paper. The zero face of the slab is referenced to the transmitting antenna position and contains the horizontally placed array of plasma tubes. Thus at the zero azimuth for the charts in Figure 42, the horizontal tubes face the transmitting antenna and the vertical tubes face the receiving antenna. It should be recalled while studying these patterns that the plasma slab lies in a vertical plane rotated about a vertical axis.

Several general statements may be made regarding the data contained in these charts. The second harmonic level and propagation direction is dictated largely by the polarization plane of the transmitted signal. Horizontally polarized incident signals are capable of yielding larger values of second harmonic signal than vertically polarized ones for a vertical plasma face. Horizontally polarized incident signals generate

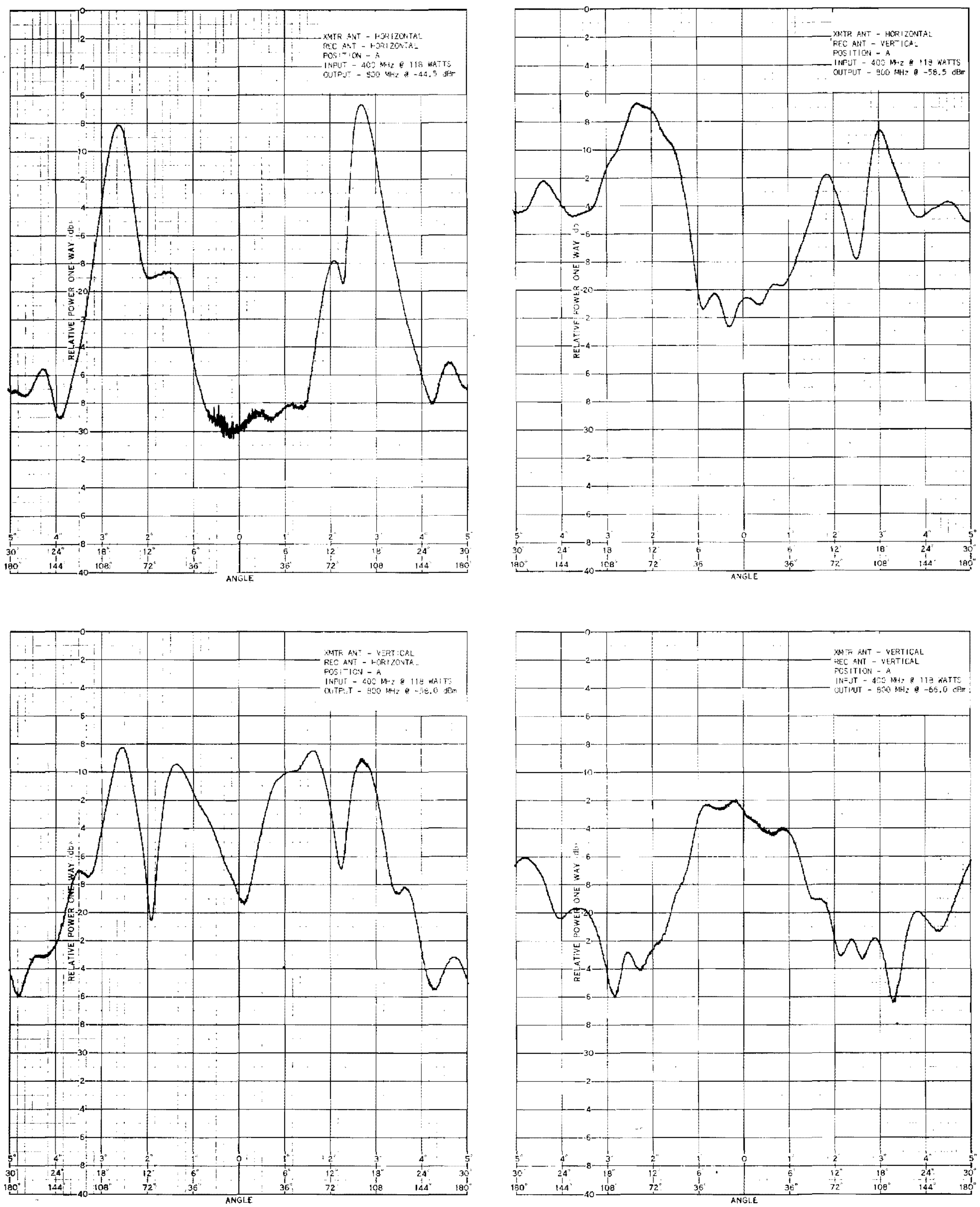

Figure 42. Second Harmonic Patterns for Plasma Slab Using Yagi Probe Antennas On Line.

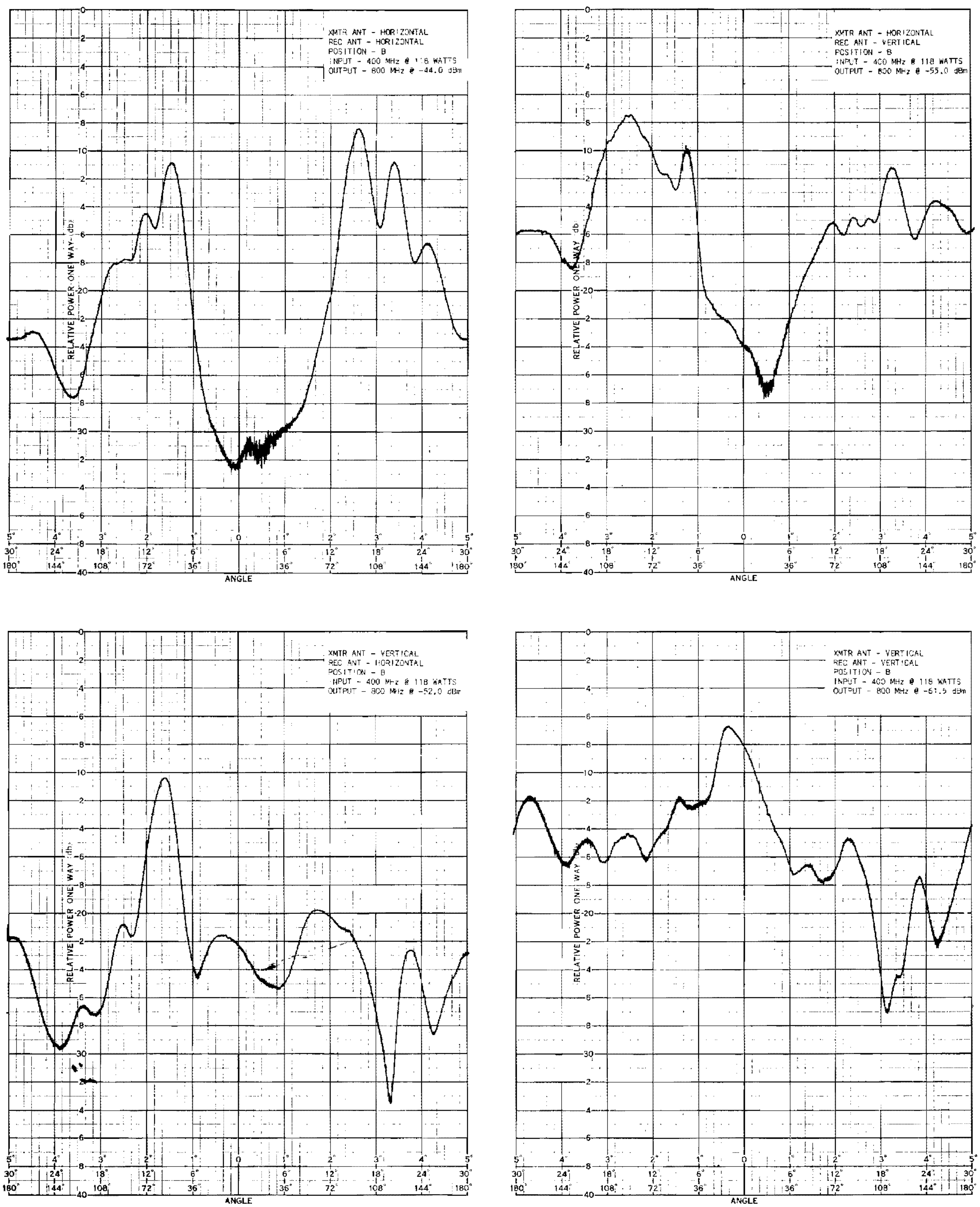

Figure 43. Second Harmonic Patterns for Plasma Slab Using Yagi Probe Antennas 45 Degrees Off Line.

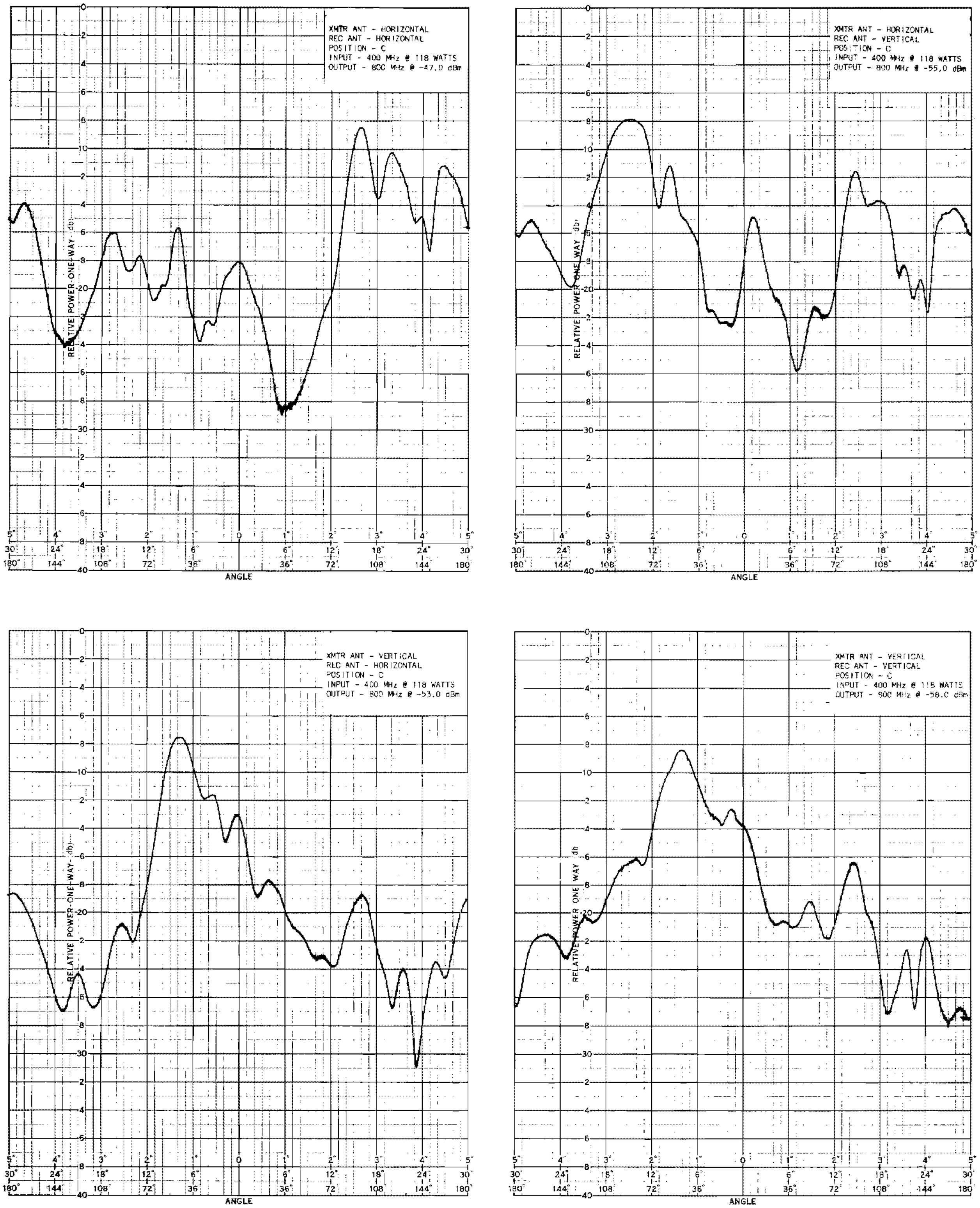

Figure 44. Second Harmonic Patterns for Plasma Slab Using Yagi Probe Antennas 90 Degrees Off Line.

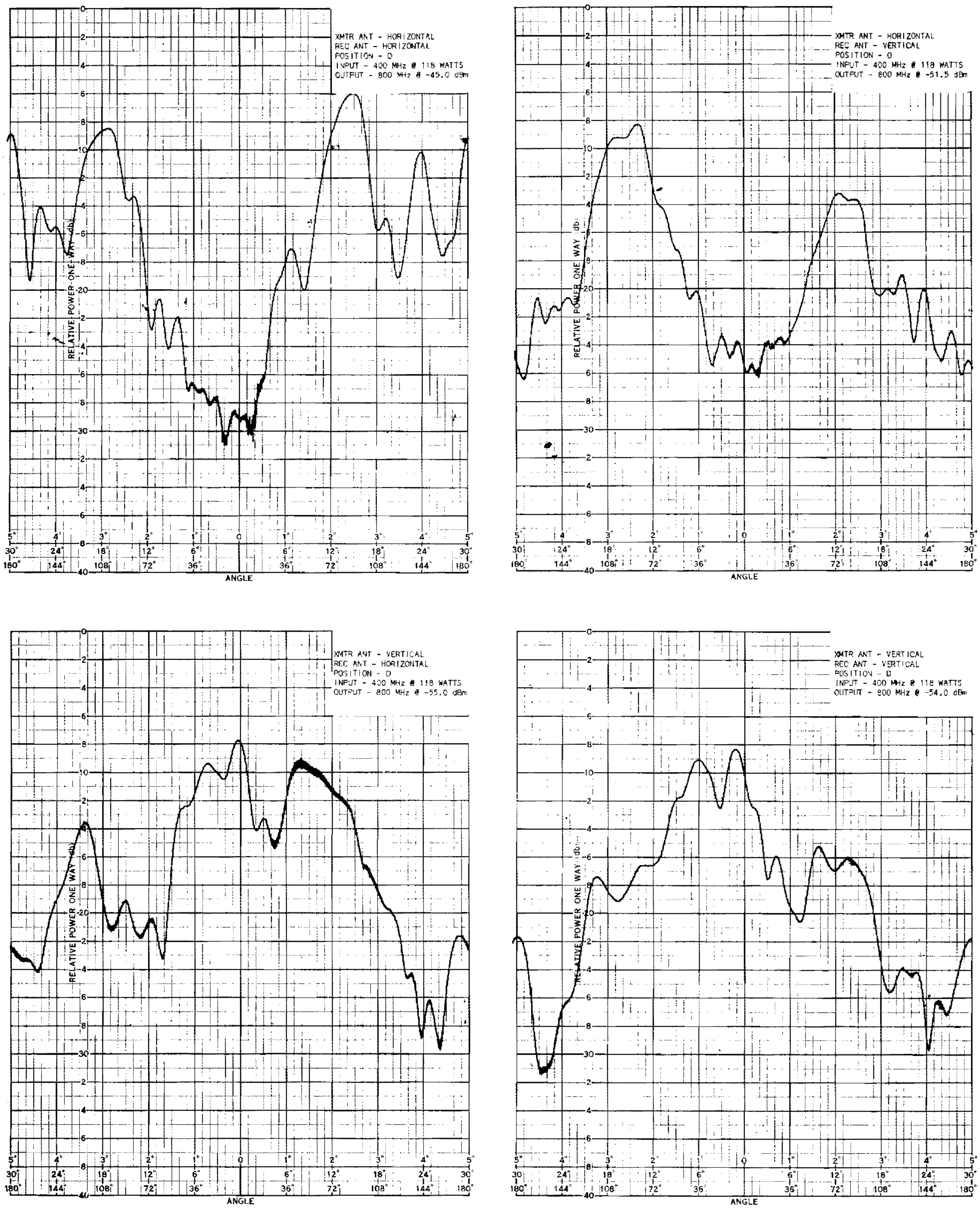

Figure 45. Second Harmonic Patterns for Plasma Slab Using Yagi Probe Antennas 135 Degrees Off Line.

their maximum second harmonic signal levels when traveling parallel to the plasma face while vertically polarized ones generate their maximum second harmonic signal levels when traveling perpendicular to the plasma face. For either incident polarization, the second harmonic is radiated in both polarizations. For horizontal incident signals, both the vertical and horizontal component of the radiated harmonic tend to propagate maximally in a direction parallel to the plasma face. The horizontal component travels essentially equally in either the forward or the reverse direction while the vertical component appears to travel maximally in the reverse direction, i.e., back toward the horizontally polarized transmitting antenna. For vertical incident signals, both the vertical and horizontal component of radiated harmonic tend to propagate maximally along the line of equi-angular reflection from the face of horizontal tubes. A minimum for both components is noted under the same conditions for the face of vertical tubes. Generally, the maximum second harmonic levels attained for either plane of incident polarization were generated from the face of tubes lying perpendicular to the electrical vector of the incident wave.

Figure 46 shows patterns indicating the effect of the plasma slab on the propagation of the fundamental or incident signal in two planes of polarization. It also presents data by which the slab tests may be compared to the dipole tests previously discussed. The patterns in Figure 46 were made using the Empire 105 tuned dipole antennas at 400 MHz.

The first two charts indicate that an electromagnetic wave will travel along the plasma surface with the electric vector perpendicular to the surface. Attenuation in this mode amounts to some 8 dB over that with no

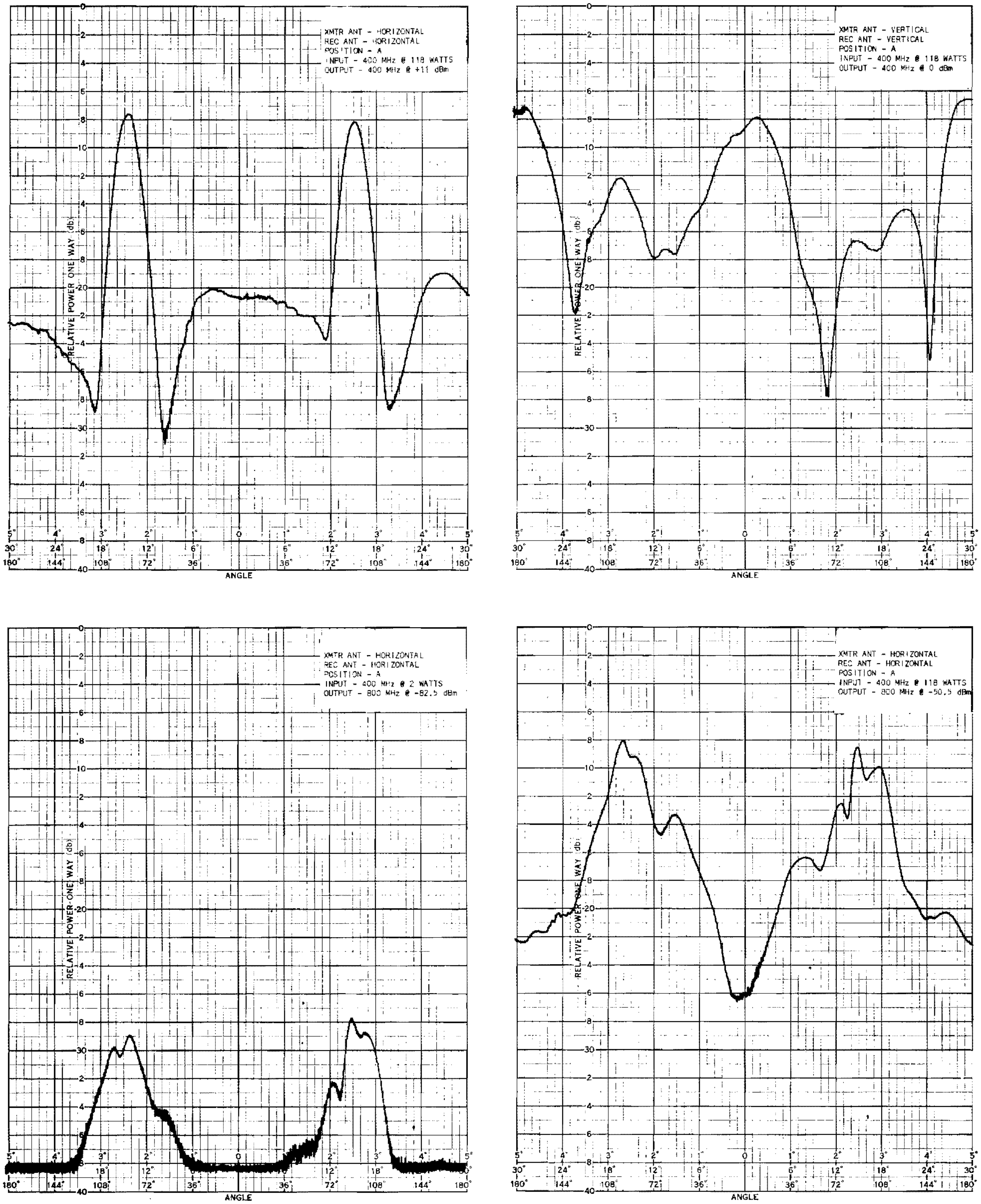

Figure 46. Fundamental and Second Harmonic Patterns for Plasma Slab Using Tuned Dipole Probe Antennas On Line.

plasma slab present. Propagation through the slab is about 19 dB below that with no slab present for either polarization. An electromagnetic wave propagates the most poorly when the electric vector is parallel to the plasma surface. In these respects the plasma slab is very similar to a conducting surface having finite conductance.

The last two charts of Figure 46 show on line harmonic levels using tuned dipoles at two incident power levels. The ratio of fundamental power levels is some 17 dB while the ratio of peak harmonic level is 32 dB. The latter ratio is very nearly double the former, indicating straight line harmonic behavior. The peak harmonic level measured for the 2 watt fundamental compares favorably with the peak levels measured near 400 MHz using the plasma-metal dipoles. The radiated harmonic level is equivalent to -40 dBm into a tuned dipole at 800 MHz.

III. DISCUSSION

A. Analysis of Closed System Data

The test results from Sections A and B of Chapter II demonstrate several important facts concerning the phenomenon of harmonic or intermodulation distortion in plasmas. It is shown that under conditions of good signal coupling and low plasma loss, second and third harmonic distortion in excess of one percent can be generated within a plasma. Conversion efficiencies as high as 25 percent have been reported for the second harmonic in extremely low pressure plasmas by Krenz and Kino.[11] The regions in which high conversion efficiencies are obtained lie well above the regions of linear proportionality wherein the intermodulation level can be predicted from the harmonic level of like generating order.[12] Furthermore, it is probable that the nonlinear mechanism at the points of high conversion efficiency is reactive, since the plasma losses can account for almost all the lost energy. A slight peaking of the harmonic level at the harmonic resonance of the center fed plasma-metal dipoles is a further indication of parametric or reactive nonlinear media. Two signal tests at power levels equivalent to those generating high percentages of harmonic distortion must be performed before the behavior of intermodulation distortion can be determined.

The coaxial coupler tests reveal that the level of harmonic distortion and the break point of linear proportionality may be a function of pressure as well as electron density. The dependence on electron density is conclusively demonstrated in the graphs of Figures 5 through 13 where values are shown for changes in the excitation current. Power transfer to the plasma and the losses sustained within the plasma are also shown to vary with electron density in Figures A-3 through A-5 of the Appendix.

The tests conducted at high level on seeded flame plasmas at atmospheric pressure are indicative of the role of pressure in the determination of harmonic distortion. In these tests, however, no firm knowledge of the electron density of the plasma is available. The temperature is known to be sufficient for the production of free electrons but the pressure also controls the ionization level[13] and the combination of unknowns confounds the issue. Further testing with glow discharges at various pressures should provide insight into the question of the pressure parameter.

The coupled harmonic tests tend to indicate that the harmonic level generated at any point along the propagation path of a fundamental wave traveling on or in a plasma is a function of the level of the fundamental signal at that point. These newly generated signals probably travel along the plasma at a rate different from that of the fundamental wave.[14] An interference pattern or standing wave is thus generated at the surface of the plasma at the harmonic frequency. The harmonic signal should therefore propagate in both the forward and the reverse direction along the plasma surface. This surmise is born out by data taken under contract No. NAS10-2639 and by the data from the radiated tests of the plasma slab.

B. Analysis of Radiated Test Data

The results from double radiated tests on dipole configurations shows that macroscopic physical dimensions create resonances that can enhance the production of harmonic distortion by a plasma medium. In fact, the production of interference to electronic devices by harmonic distortions in plasma media is brought into the realm of possibility under radiated coupling conditions through the effects of macroscopic resonance. Of course, the phenomenon may not be significant to the main engine plume because its resonant frequency would be too low to produce frequencies in the telemetry bands of the vehicle. However, antenna breakdown or ionized control jets might produce plasmas with physical dimensions appropriate to the frequencies in question.

Large plasma surfaces, as simulated by the plasma slab, apparently produce a lower peak level of harmonic than is attained at resonant lengths. The slab tests indicate that harmonic distortion is due largely to the interaction between the plasma and waves which travel along the plasma surface with the electric vector perpendicular to the surface. The harmonic signals generated in this manner also propagate along the plasma surface with the electric vector perpendicular to the surface in both the forward and the reverse direction.

It is difficult to determine to what extent the data was disturbed by the composite nature of the slab. That it was disturbed is evident from the differences in signal level radiated from the two sides of the slab for equivalent conditions of propagation. The harmonic generation was enhanced by tubes lying in polarization opposite to that of the incident signal. It is felt that in this manner the electric field was able to travel perpendicular to the plasma surface between the tubes and so generate harmonic signals. When the electrical vector is parallel to the tubes it meets a conducting surface and is probably reflected almost totally. Surface wave propagation appears to be the mechanism by which maximum harmonic distortion occurrs. In view of these findings it might be revealing to conduct the plasma dipole tests again using vertical polarizations of the probe antennas.

IV. CONCLUSIONS AND RECOMMENDATIONS

Experimental evidence demonstrates that a low pressure glow discharge plasma will generate a high percentage of second and third harmonic distortion when an electromagnetic wave travels on the plasma surface. The amount of harmonic generated in a given instance is a function of the incident power level, the electron density, the collision frequency, and the physical dimensions of the plasma. Maximum harmonic distortion is realized under the general conditions of small electron density (with regard to the operating frequencies), low collision frequency, and close coupling to the plasma.

No conclusive evidence of harmonic distortion in an atmospheric flame plasma has yet been demonstrated. It has been shown, however, that atmospheric flame plasmas seeded with alkaline materials are extremely lossy compared to low pressure glow discharges in noble gases. Electromagnetic coupling to these flame plasmas is poor using close proximity helix couplers, although results are in the range of measurement capability. The lack of nonlinear activity and the poor coupling are probably the result of the high loss and low conductivity associated with the relatively high pressure of atmospheric flames. Theoretically, flame plasmas at low pressures will behave more like the low pressure glow discharges, and limited experimental evidence suggests that the theory is correct.

The testing apparatus used under contract No. NAS10-2639 and the present contract has not been sophisticated enough to conduct an accurate study of the isolated effects of the various plasma parameters. It is recommended that such studies be performed with regard to electromagnetic distortion in plasmas, especially with regard to the pressure parameter. Though a rocket plume may generate no significant interference from nonlinear distortion products at ground level, the evidence thus far indicates that it may do so as the pressure diminishes during ascent. In fact at very low pressures (near space) any ionized gases near the vehicle will be capable of so doing.

V. APPENDIX

Description of Test Apparatus

A. Development of Silica Lined Coupler

In order to obtain close electrical coupling between a helix and a plasma, the plasma should completely fill the cylinder of the helix.[15] A hot flame plasma of the type generated by a miniture oxygen-hydrogen rocket engine cannot be allowed to contact such a metallic helix yet must be very close to the helix for good coupling. It was decided that the helix might be sufficiently protected from the devastating effect of the extremely hot, high velocity, gases by a tube of slip cast silica through which the plasma could flow in close proximity to the helix. To further aid in carrying away heat, a silica venturi was designed to follow the tube to jet pump cooling air around the exterior of the helix and silica liner.

The silica tube was designed to be 18 inches long and 1 1/2 inches in outside diameter at the flame entrance end of the tube. In order to slip cast the tube, a 1/2 degree taper of the outside diameter was required which narrowed the exit end slightly. In addition a neck enlargement was cast onto the entrance end to prevent lateral motion of the tube in the coupler shell. The neck caused considerable difficulty in the slip casting process and later had to be removed from the mandrel. The tube taper was sufficient to prevent lateral motion within the coupler shell.

The mandrel used to form the slip casting molds was used to wind the twenty-seven turn helix from 3/16 inch copper tubing. Winding was begun at the narrow end of the mandrel and the turns were worked toward the larger end so that the helix fit snugly against the silica counterpart. The helix was wound with equal spacing between turns which resulted in a gradual change of pitch angle along its length.

The silica tube was supported at each end by three adjustable posts such that it lay coaxially within a 3 inch ID aluminum shell. The tube was protected at the points of support with a single layer of asbestos tape such that the posts could clamp the tube in place. The shell was made of 3 inch aluminum pipe which had been milled into 3 foot hemi-cylinders and pin indexed to form a complete cylinder. One of these hemi-cylinders was spot faced on the outside and drilled to take two type N panel jacks for the terminal connections of the helix. The two halves of the shell were clamped together with five bands made up of large diameter hose clamps. Two of these further served to lock the shell into a cradle which supported it on the test bench.

A 30 degree by 15 degree nozzle venturi was cast of silica and fitted within the shell some 4 inches beyond the helix. The venturi was locked in place by three studs which fit into a grove around the circumference of the nozzle. The action of the rocket exhaust moving through this venturi pumps a large volume of air around the helix and cools the aluminum shell. Figure A-1 and A-2 are photographs of the silica lined helix coupler in test position and broken down.

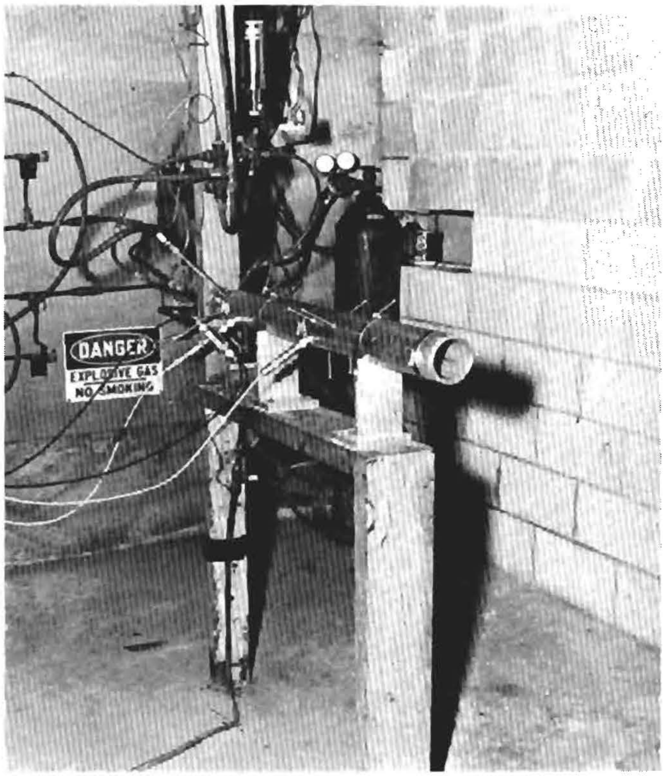

Figure A-1. Assembled Coupler in Test Position.

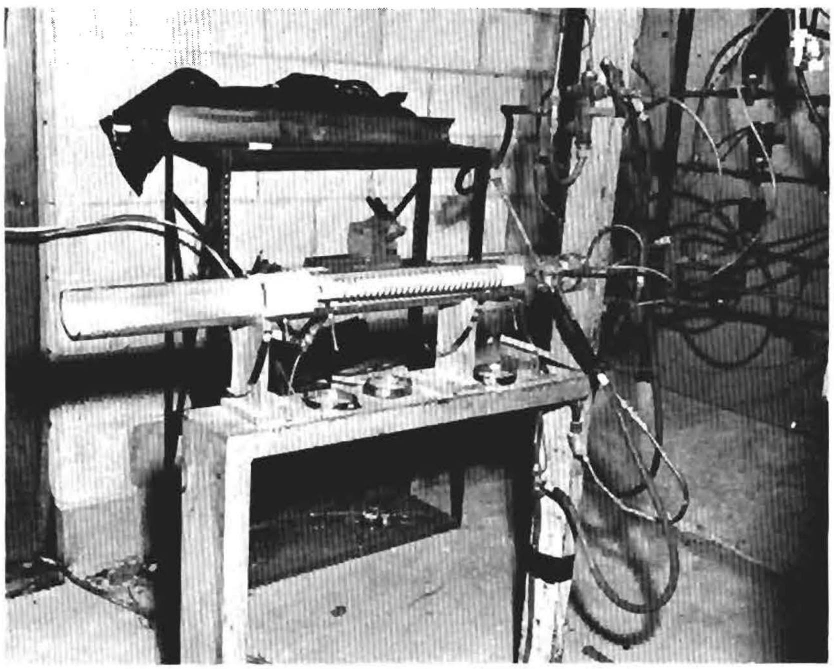

Figure A-2. Breakdown of Coupler in Test Position.

Initial flame tests of the coupler showed that the helix needed additional cooling so a water connection was placed at either end of the helix. The water was introduced to the helix through a plastic tube at the engine end of the coupler and exited into the stream of gases at the far end of the helix. With water cooling, the helix could withstand runs in excess of 30 seconds. The silica tube, however, would glaze after some 20 to 30 seconds and sag into the flame path.

The silica tubes were originally cast some 1/16 inch thick but a high breakage rate required that the thickness be increased to 1/8 inch. The thin tubes could not withstand the pressure of the engine shock front on firing. Several helices were destroyed because of broken silica tubes due either to overheating or shock fracture. The maximum continuous operating time was set at 15 seconds which allowed about eight runs before tube fracture.

Prior to the completion of the silica tubes, a twenty-seven turn helix of 3/16 copper tubing was wound on a 1 1/2 inch diameter glow discharge tube which was centered in the coupler shell using the silica tube support posts. One of the TM launchers from the coaxial coupler used in contract No. NAS10-2639 was fitted at the engine end of the coupler. The other end of the coupler was left open. This configuration was used to test the coupling characteristics of the twenty-seven turn helix.

Figures A-3 and A-4 show the VSWR characteristics at ports 1 and 2 respectively for both dc and rf excitation. Useful coupling is achieved for frequencies between 50 MHz and 1300 MHz for most conditions of excitation tested. Figure A-5 shows the insertion loss characteristics

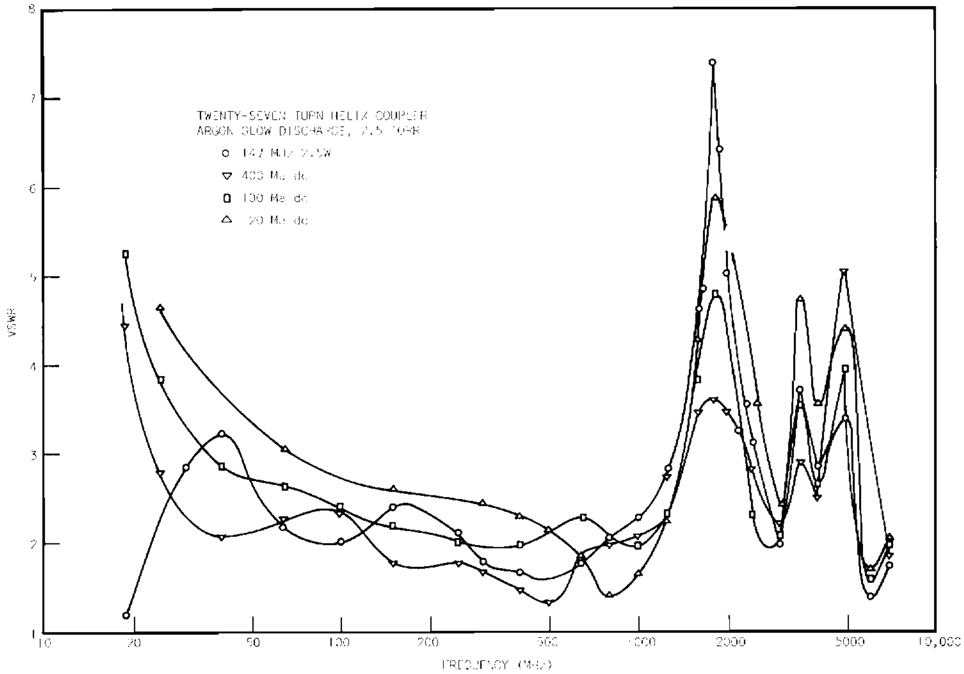

Figure A-3. VSWR Characteristics for the Twenty-Seven Turn Uniform Helix Coupler on 2.5 Torr Argon Glow Discharge - Port No. 1.

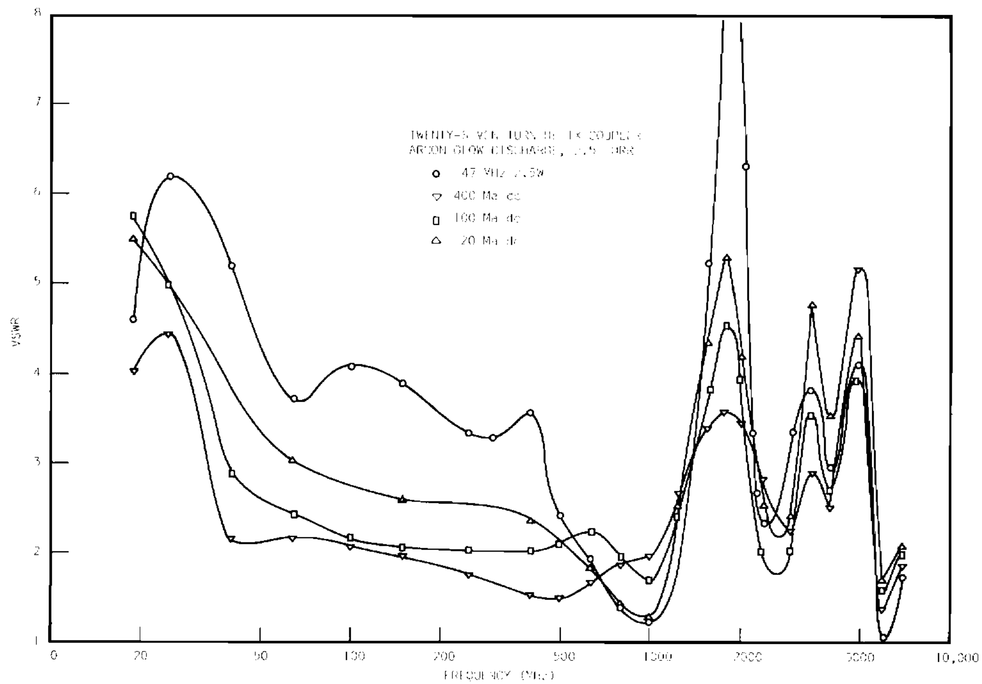

Figure A-4. VSWR Characteristics for the Twenty-Seven Turn Uniform Helix Coupler on 2.5 Torr Argon Glow Discharge - Port No. 2.

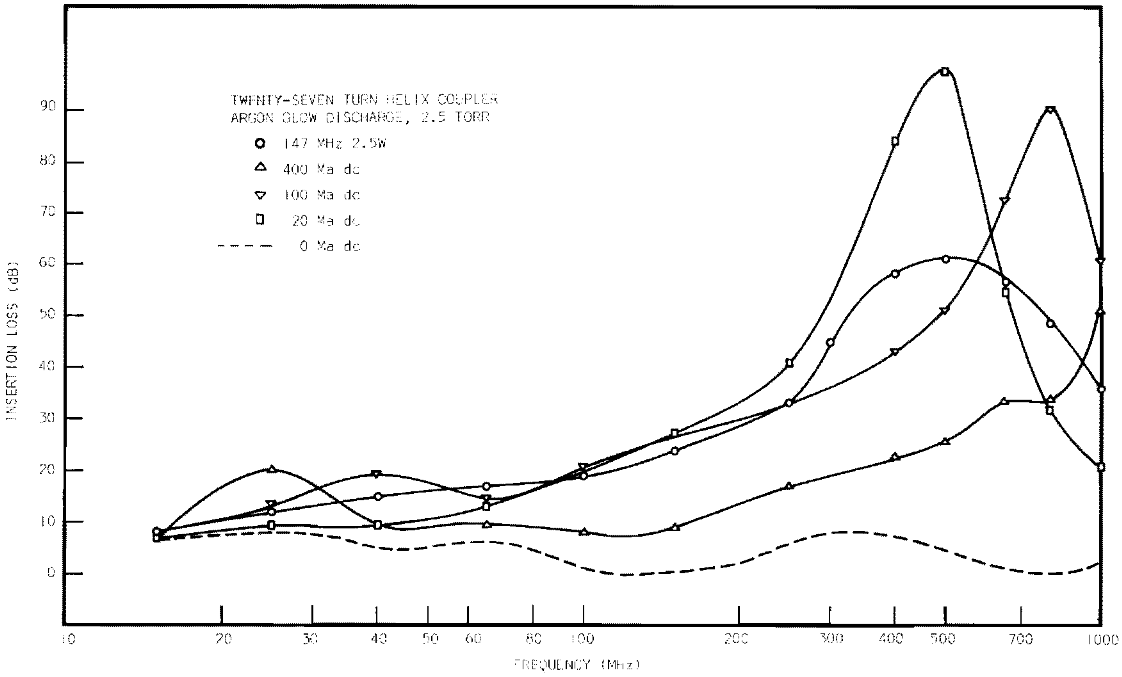

Figure A-5. Insertion Loss Characteristics for the Twenty-Seven Turn Helix Coupler on 2.5 Torr Argon Glow Discharge.

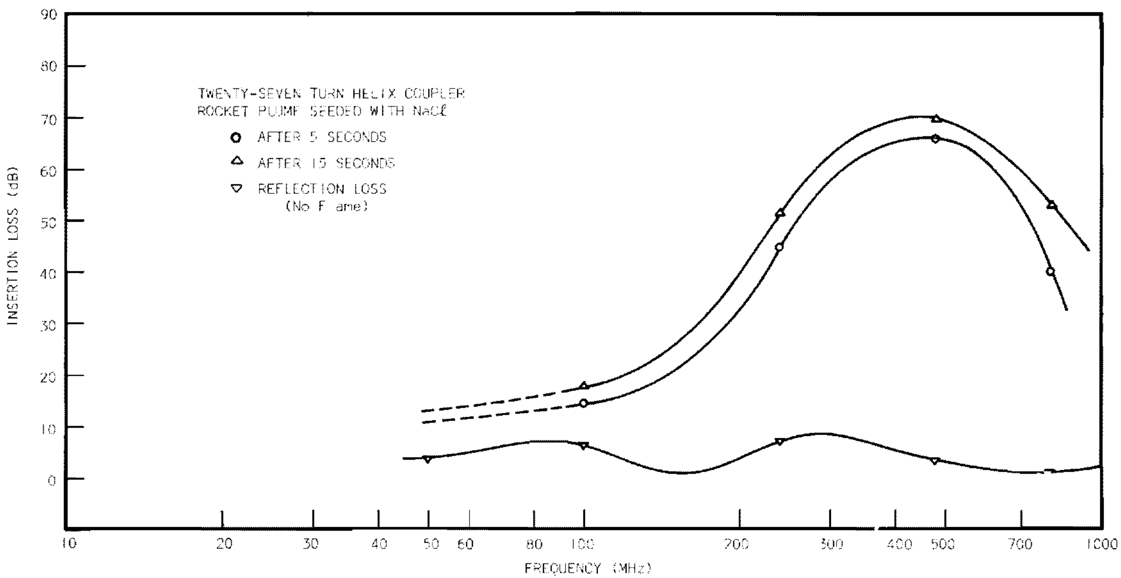

Figure A-6. Insertion Loss Characteristics for the Twenty-Seven Turn Helix Coupler on Flame Plasma Seeded with Sodium Chloride.

for the different conditions of excitation over the useful band of frequencies. The frequency of peak loss is seen to move with changes in the electron density (proportional to dc excitation).

Figure A-6 shows the limits of insertion loss measured with the silica lined helix over a flame plasma seeded with sodium chloride. No comprehensive measurements of the VSWR could be made on the flame plasma because run times were not sufficiently long for bridge measurements nor the characteristics sufficiently steady during the run. It is pointed out in Chapter II that the coupling characteristics of the helix are poor with the high pressure seeded flame plasma.

B. Development of Configurations for Radiated Testing

A plasma-metal dipole configuration was fabricated using glow discharge tubes as one dipole arm and metal tubes for the other arm. Two antennas were constructed, one whose physical dimensions approximated those of a 220 MHz dipole, and another of approximately 290 MHz. The construction details of the lower frequency antenna are shown in the photograph of Figure A-7. Two 12 inch, 8 watt glow discharge tubes were paralleled as one arm of the dipole, while the other arm consisted of two parallel copper tubes whose length and diameter approximated those of the plasma tubes. The 290 MHz antenna was constructed in a similar manner, using 9 inch, 6 watt, glow discharge tubes.

Excitation for the glow discharge tubes was accomplished by connecting the two tubes in series and then energizing in a normal manner, i.e., as if the series combination of the two tubes were only one tube. The rf

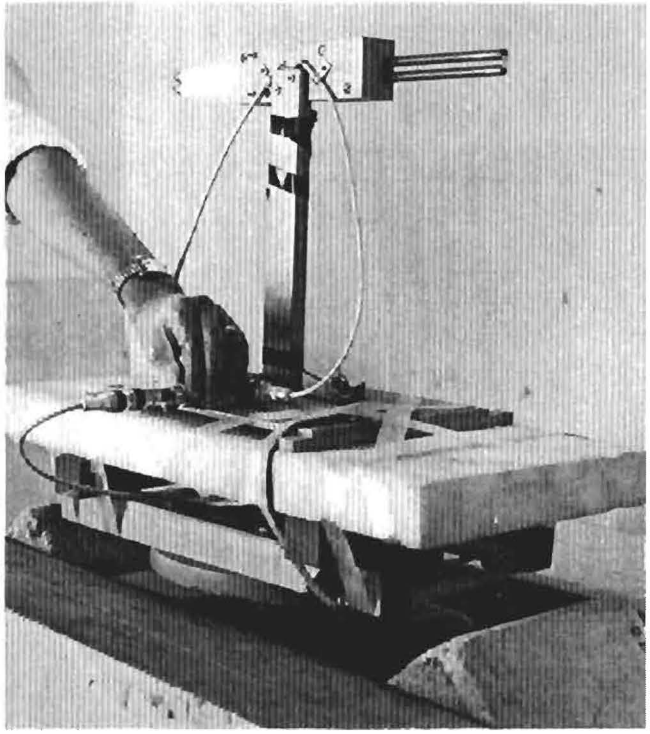

Figure A-7. Plasma-Metal Dipole on Turntable.

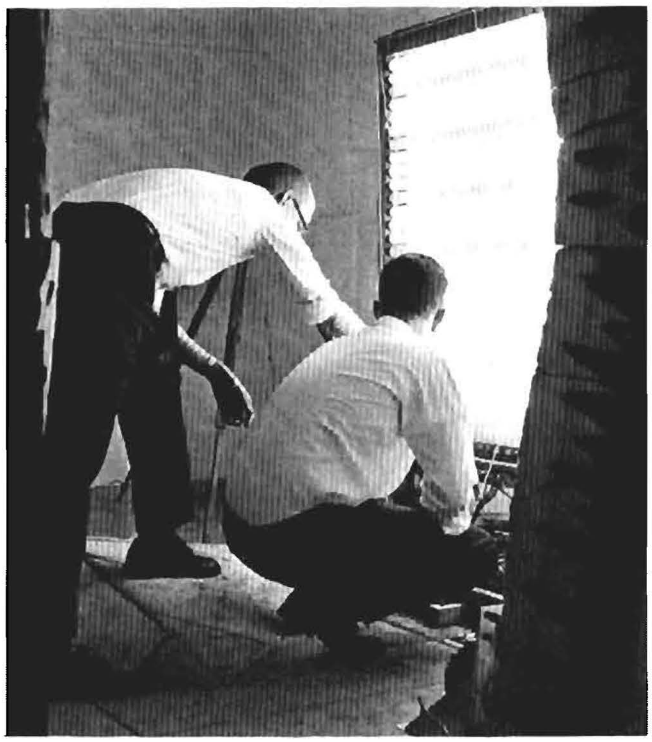

Figure A-8. Plasma Slab in Anechoic Chamber.

signal input was capacitively coupled to both tubes in parallel, and choke isolated from the excitation supply voltage. When the plasma-metal dipole was tested as a center fed antenna, the plasma arm and the metal arm were connected to an Anzac Model H-1 hybrid, which enabled the dipole to be operated in a balanced condition. During other radiated tests which were performed, the hybrid was removed and the plasma arm was ac coupled directly to the metal arm.

A plasma slab, shown in the photograph of Figure A-8, was constructed of fifty-six, 48 x 1 1/2 inch, 40 watt, glow discharge tubes. Twenty-eight of the tubes were mounted horizontally as shown in Figure A-8. The other twenty-eight were mounted vertically, directly behind the horizontal bank, thus giving a slab of plasma whose dimensions are approximately 48 x 48 x 3 inches. Provisions were made for individual control of the excitation of each tube such that any tube or combination of tubes could be turned on or off as desired.

The transmitting antenna utilized during the plasma slab tests was an 8-element, 400 MHz Yagi, and the receiving antenna was a 16-element, 800 MHz Yagi. The driven element of the transmitting Yagi was a folded dipole fed from an unbalanced 50 ohm source. The driven element for the receiving Yagi was also a folded dipole, connected in a balanced condition from an Anzac H-1 hybrid. The patterns for both of these antennas are shown in Figure A-9.

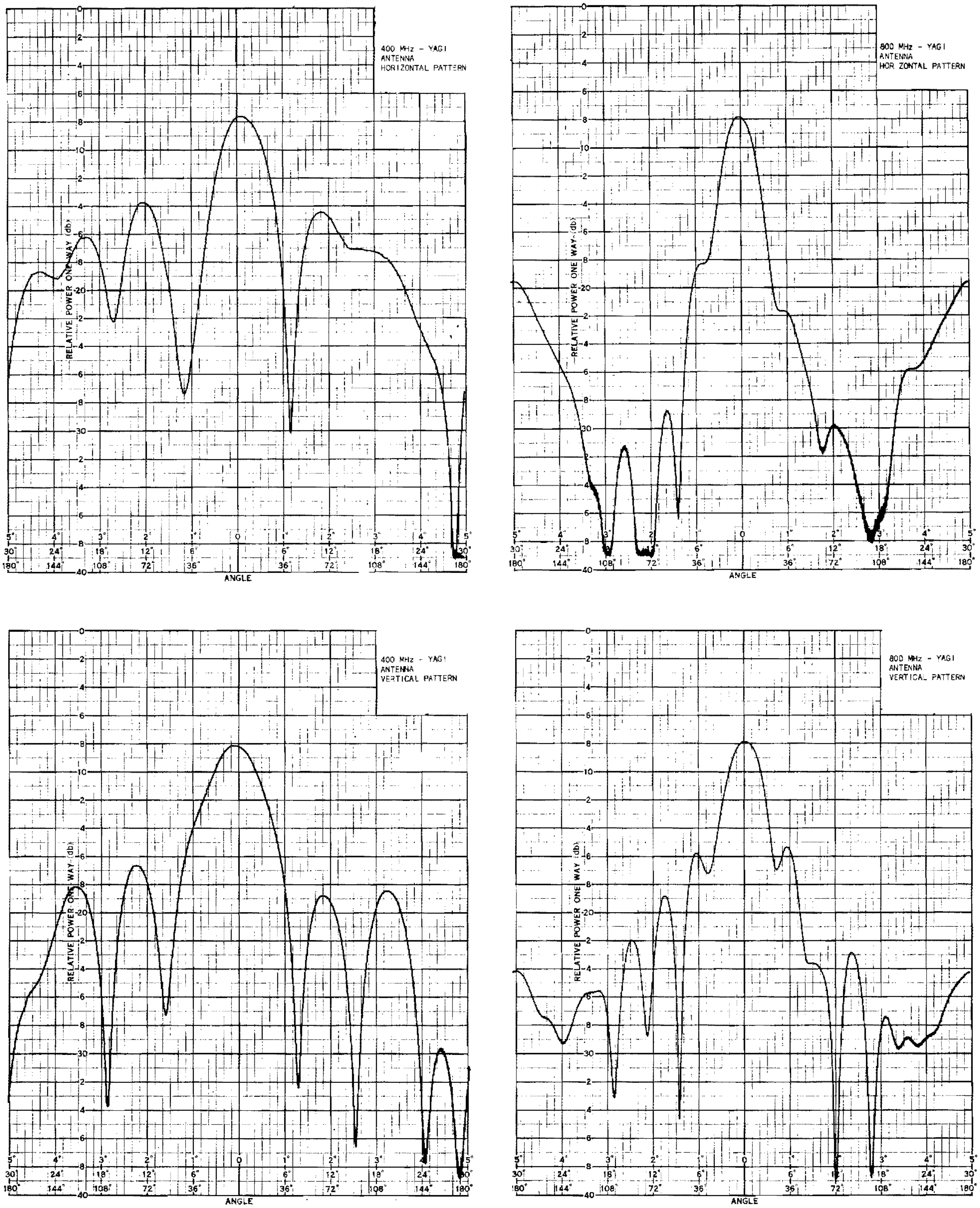

Figure A-9. Antenna Patterns for Yagi Probe Antennas.

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